Technical Report REMR-CS-62
March 1999

US Army Corps of Engineers
Waterways Experiment Station

Repair, Evaluation, Maintenance, and Rehabilitation Research Program

Performance Criteria for Concrete Repair Materials, Phase II Summary Report

by *Alexander M. Vaysburd, Peter H. Emmons,*
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Whitlock, Dalrymple, Poston & Associates, Inc.

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Prepared for Headquarters, U.S. Army Corps of Engineers

The following two letters used as part of the number designating technical reports of research published under the Repair, Evaluation, Maintenance, and rehabilitation (REMR) Research Program identify the problem area under which the report was prepared:

	Problem Area		Problem Area
CS	Concrete and Steel Structures	EM	Electrical and Mechanical
GT	Geotechnical	EI	Environmental Impacts
HY	Hydraulics	OM	Operations Management
CO	Coastal		

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Rehabilitation Research Program

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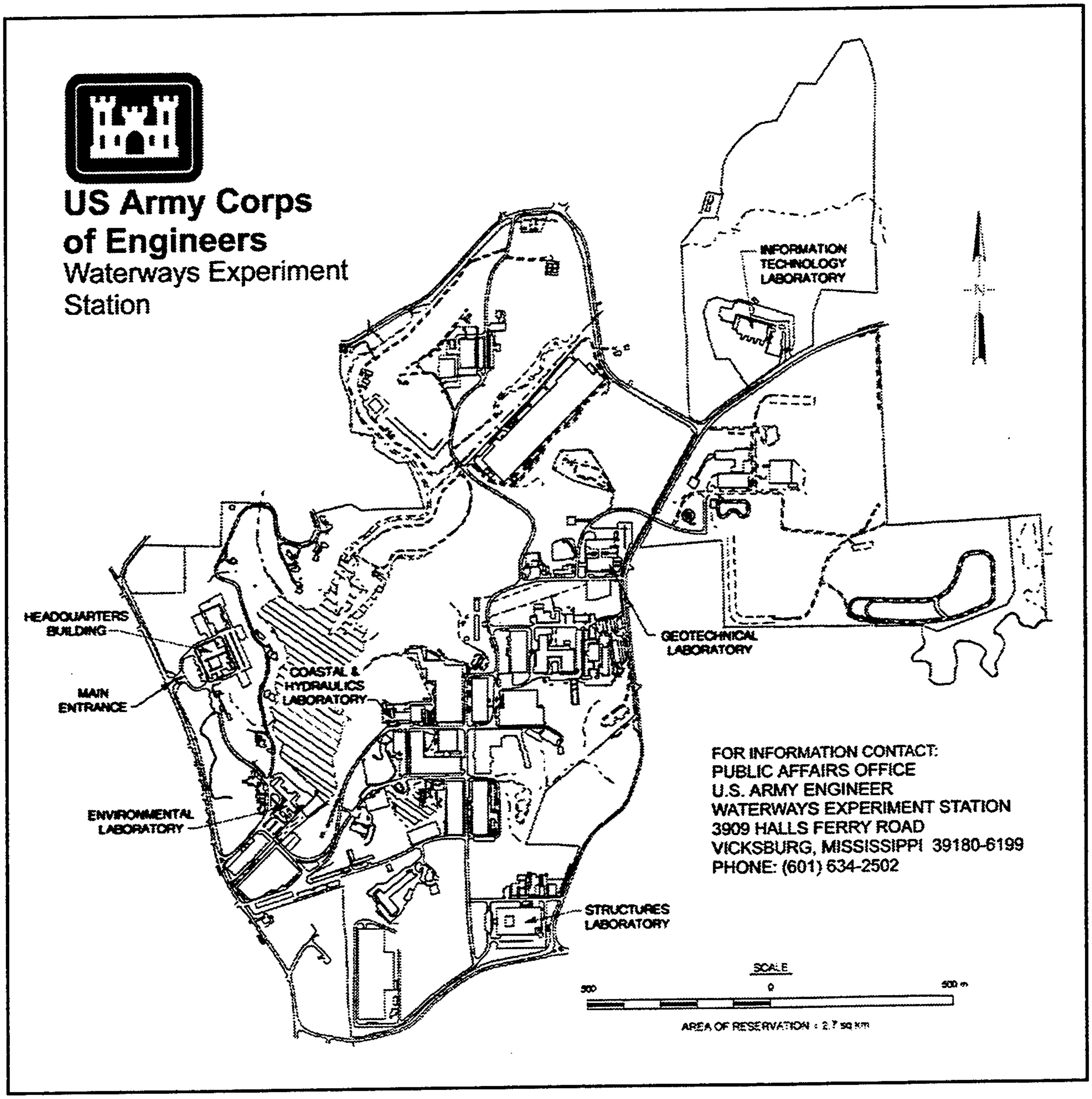

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Preface

The study reported herein was authorized by Headquarters, U.S. Army Corps of Engineers (HQUSACE), under Civil Works Research Unit 32637, "Evaluation of Existing Repair Materials and Methods," for which Mr. James E. McDonald, Structures Laboratory (SL), U.S. Army Engineer Waterways Experiment Station (WES), is the Principal Investigator. This work unit is part of the Concrete and Steel Structures Problem Area of the Repair, Evaluation, Maintenance, and Rehabilitation (REMR) Research Program.

The REMR Technical Monitor is Mr. M.K. Lee, HQUSACE. Dr. Tony C. Liu (CERD-C) is the REMR Coordinator at the Directorate of Research and Development, HQUSACE). Mr. Harold C. Tohlen (CECW-O) and Dr. Liu serve as the REMR Overview Committee. Mr. McDonald is the Problem Area Leader for Concrete and Steel Structures.

The study was performed by Structural Preservation Systems, Inc., Baltimore, MD, under contract to WES. The study was under the direct supervision of Mr. McDonald and general supervision of Dr. Paul F. Mlakar, Chief, Concrete and Materials Division, and Dr. Bryant Mather, Director, SL.

The authors acknowledge the substantial contributions by Mr. Miroslav Vadovic, Structural Consultant, in the theoretical analysis of depth of coring; Mr. Ruben Bernal, Structural Preservation Systems, Inc, Illinois Office, for his dedication and hard work during the field testing in Florida, Illinois, and Arizona; and Ms. Margo Gray, Structural Preservation Systems, Inc., Corporate Office, for her assistance in the completion of the report.

Discussions in this report relating to any product named must not be construed as a testimonial or endorsement of that product. As a consequence, readers are cautioned not to make reference in an advertisement to any tests that have been made.

At the time of publication of this report, Acting Director of WES was COL Robin R. Cababa, EN.

Technical Report REMR-CS-62 Performance Criteria for Concrete Repair Materials, Phase II

Key

Material No.	Manufacturer	Product Name	Generic Classification
1	Fosroc, Inc.	Patchroc 10-16	Fast-setting, high-early strength concrete
2	American Stone-Mix, Inc.	Metro 240	High-early strength concrete
3	Conproco Coatings	One Shot	Polymer-modified concrete
4	Five Star Products, Inc.	Structural Concrete	High-early strength concrete
5	W.R. Grace & Co.	FasTrak	High-strength, rapid-setting mortar
6	The Euclid Chemical Co.	Euco SR-93	Polymer-modified silica-fume mortar
7	Conproco Coatings	Conpro-Set	Polymer-modified concrete
8	Fosroc, Inc.	DN-116	Polymer-modified, fiber-reinforced mortar
9	Packaged by American Stone-Mix, Inc.	Control Concrete Mixture (MD DOT Mixture 6)	Portland-cement concrete
10	Master Builders, Inc.	Emaco R310	Polymer-modified concrete
11	Master Builders, Inc.	Emaco S66-CR	Cement-based concrete
12	Sika Corp.	SikaTop III Plus	Polymer-modified concrete

1 Introduction

Background

The deterioration of existing concrete structures, the necessity to repair a very large stock of deficient concrete structures, the premature failure of repairs, and the need to improve repair durability in a cost-effective way are among the major problems we are facing today.

Durability of a repaired concrete structure and its service life depends to a large degree on the behavior and coexistence of a repair material and the existing concrete substrate combined together in a composite system – in a repaired concrete structure.

Deterioration and distress of repaired concrete structures are a result of a variety of physico-chemical processes, the most serious of them that lead to premature failures are caused by cracking of the repair. Restrained contraction of repair materials, the restraint being provided through bond to the existing concrete substrate, is a major factor leading to cracking and delamination of the repair phase. In simple terms, the repair material cracks when tensile strain exceeds the tensile strain capacity. While development of tensile cracks may be favorable from the point of view of stress distribution in the texture of a material, the situation becomes very different when judged from the point of view of the permeability– its capacity to retard penetration of aggressive elements into the concrete.

Cracking accelerates the penetration of aggressive substances into the existing concrete and repair, which in turn aggravates any one or a number of other mechanisms of deterioration. For example, in repeated cycles of freezing and thawing in a wet environment, water will enter the cracks during the thawing portion of the cycle only to freeze again later, and there will be progressive deterioration with each cycle.

Concrete repair is a complex living system, with constantly changing properties. The behavior of repair material in real life is the result of interactions of its properties with properties of existing concrete substrate and between many variables of exterior and interior environments acting simultaneously.

Under current practice, there is no guidance to the selection of repair materials for intended use, just as there are no performance criteria for the selection of repair materials dimensionally compatible with the existing structure. The selection process is usually based on information from the manufacturer or experience of consulting engineers and specialist contractors.

Current emphasis in the specification of repair materials is on the relatively short-term properties such as strength, bond, and early volume changes. Although these properties indicate immediate performance of the repair, they give little information with respect to its long-term performance with respect to cracking and efficient composite action with the substrate to carry applied loads and deformations.

Materials should be classified based on their ability to resist cracking. The idea is not simply to "classify" but rather to emphasize that there are property differences which can lead to application and service problems. The choice of the best material for a given application is, of necessity, an optimization. It, therefore, should be carried out with as full a knowledge as possible of the relevant properties. The reliable source of these properties must become material data sheets.

While the economics and difficulties of carrying out repairs provide a strong argument for researching the performance of repair systems, there are some difficulties that may be attributed to the following factors: (a) each of the broad categories of repair materials has a wide variation of properties within it so that there are no representative materials; (b) performance testing requires representative repairs to be exposed to a real world environment for realistic durations; and (c) repair materials are continually under development – by the time studies have been completed, materials have already been changed.

To this end, it was recognized that research on a few reasonably representative repair materials would provide valuable basic information on the parameters controlling repair material behavior and, specifically, durability. It would also provide a benchmark behavior against which the properties of more recently developed materials and materials developed in the future could be judged. It is within this context that the present study was proposed.

With the variety of ways now possible to achieve a given level of performance, there is considerable pressure within the industry to develop and use performance criteria. Unfortunately, development of such criteria has not kept pace with the development of materials, primarily because of the lack of appropriate scientific and field data needed for its development. Development and adherence to sound performance criteria can be an avenue to improve the repair field. Introduction of performance criteria will require improved understanding of the relationships between the composition, microstructure, and physical performance of cement-based composites. Dimensional compatibility between a repair and an existing structure is a hallmark of such criteria.

To specify the appropriate material and to evaluate performance of products are virtually impossible at this time because to the variety of methods which measure the shrinkage of materials. In addition to the absence of a reliable industry-wide testing method, manufacturers who are using the same standard method are arbitrarily modifying the method. The arbitrary application of test methods has resulted in controversy and confusion in selecting and specifying materials.

The ultimate objective of all performance testing of concrete and other repair materials is the prediction of how the material will function in the field through evaluation of how it functions under test in the laboratory. Material tested in the laboratory is not identical with that tested in the field due to many causes, and forces exerted by nature are different in type, duration, and severity.

The report addresses the so-called nonstructural, protective types of repairs. The discussions herein are confined to what might be termed zero-stress conditions; i.e., where no external stresses such as compression, tension, etc., are applied. They, therefore, exclude deformation under load, heat distortion, and similar procedures where deformations result from externally applied stresses.

Repair materials are considered critically from the standpoint of dimensional compatibility or incompatibility (mismatch) with existing concrete substrate. Mechanical properties and performance properties such as shrinkage, creep/stress relaxation, and sensitivity to cracking are discussed together with the analysis of laboratory testing versus service performance of experimental repairs.

The foregoing discussions are focusing on a very critical for repair durability issue – selection of repair materials. However, it should be strongly emphasized that material is only one of the critical components of the durable repair system. Design and field operations are equally important. Material, per se, does not perform; the end product made from the material performs. Materials value lies in that they permit an engineering product to fulfill its functions. To produce this engineering product, a repaired concrete structure that is long lasting and satisfies the intended use, design, and workmanship are equally important. To achieve a high-performance repair, it takes much more than a "good" material. It takes all that influences the high performance. Poor design and shoddy workmanship, combined with aggressive exposure conditions, all too frequently lead to premature deterioration of concrete repairs.

The objective of any repair project should be to produce a durable product at a relatively low cost. Some important aspects of such a project should encompass the following steps:

a. Assessing the cause(s) of deterioration/distress.

b. Assessing the condition of the existing structure (degree of deterioration/distress).

c. Establishing the nature and severity of the interior and exterior environment.

d. Ascertaining the intended service life of the structure.

e. Evaluating and selecting an appropriate repair system.

f. Developing repair system design details and specifications.

g. Implementing the work as per specification.

It is not the intention of the foregoing to present final engineering data on the materials tested nor to pass judgement on their relative merits for any particular application. It is, however, intended to emphasize that dimensional stability depends on design and construction process as well as on materials. Guidance for the selection of such materials is offered.

Structural Preservation System, Inc. (SPS), Baltimore, MD, was awarded a research study by the U.S. Army Engineer Waterways Experiment Station (WES) to develop performance criteria and standard material data sheet protocol for use by the U.S. Army Corps of Engineers (USACE) and others for dimensional compatible repair materials. As part of the Phase I Study (Emmons and Vaysburd 1995), state-of-the-art in repair materials and related testing methods were established and a comprehensive experimental field and laboratory evaluation program for the Phase II study was developed.

The performance of selected, commercially available repair materials was evaluated under in situ differing environmental conditions. The field program was conducted to enhance an understanding of the behavior of the repair materials, especially as related to their restrained volume changes and resulting cracking. A concurrent laboratory investigation was performed in which the same 12 materials were subjected to a series of standard and nonstandard tests to determine material properties which were perceived to be of importance to provide information about their dimensional behavior.

No attempt is made in this Summary Report to give complete details of the laboratory and field testing, since such have been adequately covered in reports by Poston, Kesner, Emmons, and Vaysburd (1998) and Emmons, Vaysburd, Poston, and McDonald (1998). This report presents a summary of the field and laboratory testing and proposes a performance criteria for repair materials based on their dimensional compatibility with existing concrete and standard protocol for repair material data sheets. The overall USACE research study is outlined in Figure 1.

Objective

The principal objective of this study was to develop performance criteria for the selection of cement-based repair materials that, in otherwise equal conditions, will lead to durable and cost-effective concrete repairs. Furthermore, the project was directed toward the development of the Standard Repair Material Data Sheet Protocol. The development and then the adoption of the proposed Performance Criteria and Standard Data Sheet Protocol will give guidance to the designer/specifier and user of repair materials through confused sea-of-complex choices that are faced today.

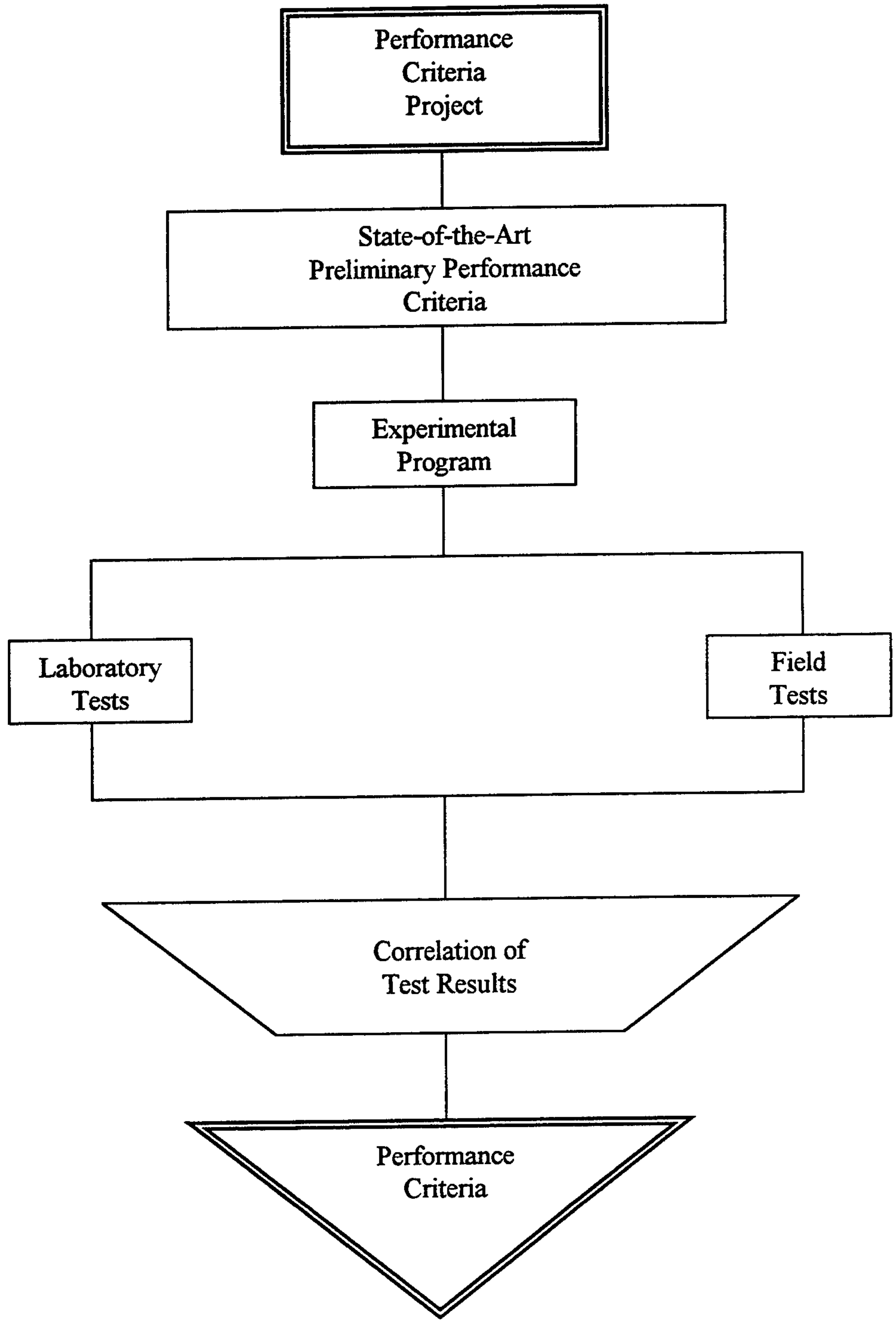


Figure 1. Performance criteria for selection of repair materials project

The main objective of this Summary Report is to determine the significance, in terms of field performance, of the numerous laboratory and in situ standard and nonstandard tests that have been performed. This determination, in turn, would define a desirable range of properties and test methods for their evaluation which have a definite effect on the performance and durability of concrete repairs.

Scope

The study was performed in two phases. Phase I of the study identified the state-of-the-art concerning the factors affecting durability of concrete repairs and material properties governing dimensional compatibility of repair materials with existing concrete. Preliminary Performance Criteria was developed based on the state of the art. Finally, the Phase I also included an experimental program for laboratory and field tests to clarify these performance criteria parameters that may reduce the sensitivity of repairs to shrinkage cracking.

Phase II of the study was conducted in two parts. One part was carried out in the field, and the other part involved laboratory work that could later be correlated to the field performance of the experimental repairs. The scope of Phase II comprised the laboratory determination of mechanical, physical, and performance properties of the 12 repair materials selected for the project, field tests, and monitoring of experimental repairs made with each of the 12 materials. Cracking tendency of the experimental repairs was investigated at three testing locations selected for this program: South Florida, Illinois, and Arizona.

The results of Phase I of the study were reported by Emmons and Vaysburd (1995). The results of the laboratory tests of Phase II of the study were recently reported by Poston, Kesner, Emmons, and Vaysburd (1998); the results of the field studies reported by Emmons, Vaysburd, Poston, and McDonald (1998).

The summary of the overall investigation, including Performance Criteria and Standard Repair Material Data Sheet Protocol are included in this report.

2 Results and Discussion

General

This chapter summarizes the results of an extensive program of research aimed at investigating compatibilities or incompatibilities between concrete and a number of repair materials. Representative commercially available cement-based repair materials were selected for the project.

Along with the field study where evaluation of sensitivity to cracking of repair materials were carried out, a detailed laboratory study was performed. The laboratory part consists of a series of experiments designed to study the performance of repair materials and practices under controlled laboratory conditions.

This chapter discusses only some of the findings of the study specifically related to establishing performance criteria for the selection of repair materials. The ability of repair materials to prevent, or more realistically minimize, the cracking is discussed.

This report is a summary of the findings of a large number of independent experiments; therefore, the detailed methodologies and results of each experiment are not included. However, they are described more fully in the field study report (Emmons, Vaysburd, Poston, and McDonald 1998) and the laboratory test report (Poston, Kesner, Emmons, and Vaysburd 1998).

Repair Materials

Eleven commercially available repair materials which are labeled 1 through 8 and 10 through 12 were used in this study, together with a plain concrete mixture (labeled 9) of normal strength which was used to provide control specimens for comparison. The selected repair materials represented two groups of cement-based repair materials: cementitious and polymer-modified – six representative materials from each group.

In this chapter, the test results are analyzed and discussed in the context of trying to establish correlation between the tests performed on small specimens in the field and in the laboratory and actual field performance of the near-job-size experimental repairs. The field performance of the repairs was judged based on their sensitivity to cracking. The results of the overall field and laboratory programs are summarized in Tables 1 and 2. All materials were mixed and applied in accordance with the manufacturers' recommendations.

Laboratory and Field Testing

The test methods used to measure the important mechanical, physical, and performance properties of the 12 selected materials are summarized in Table 3. Existing standards were employed where feasible; these will not be discussed further unless the results suggest that the method is open to question. In other cases, new test techniques have been developed or adapted specifically for the purposes of this research and are reviewed briefly below.

Except where modifications are noted, the standard tests were performed in the laboratory in accordance with the American Society for Testing and Materials (ASTM) test methods. The nonstandard methods were adopted and developed and they are identified in the Phase I study (Emmons and Vaysburd 1995) and performed in the field and the laboratory. A testing protocol was established for each of the nonstandard tests to ensure consistency in the evaluation of all materials. Some of the standard and nonstandard test methods are shown in Figures 2, 3, 4,and 5.

The size of the specimens used in this study conforms to the large sizes recommended for testing concrete instead of relatively smaller sizes permissible for repair materials. This was done for the following reasons:

a. Among the repair materials considered in the study was plain concrete with coarse aggregates and a larger specimen size was considered appropriate for comparison of properties of the different materials.

b. The research is concerned with mismatch of properties between the substrate and repair material. The specifications and design procedures of substrate concrete are established on the basis of properties determined from a standard size of test specimens of concrete. It is, therefore, appropriate to use the same size of specimens for repair materials in this investigation.

c. The experimental repairs are 76 mm (3 in.) thick, and most of the manufacturers are recommending to expand the mixtures with coarse aggregate if the repair thickness is in excess of 50 mm (2 in.).

The following are some observations and lessons learned concerning nonstandard test methods employed in the project.

Table 1
Overall Summary of Field Test Results

Material No.	Generic Type	SPS Test Maximum Deflection, mm (in.)	German Angle Observations	Repair Monitoring Observations	Conclusions
1	Cement mortar	6.60 (0.26)	No cracks	No cracks	Good crack resistance
2	Cement concrete	6.60 (0.26)	No cracks	Cracked in Arizona	Early-age cracking when exposed to low humidity and high temperature
3	Polymer-modified concrete	10.92 (0.43)	Cracked in Arizona	Minor cracking in Arizona	Susceptible to cracking when exposed to low humidity and high temperature
4	Cement concrete	5.33 (0.21)	No cracks	No cracks	Good crack resistance
5	Mortar	3.30 (0.13)	Cracked in Florida; debonded in Illinois	Cracked	Prone to cracking, particularly when not extended with aggregate
6	Polymer-modified mortar	16.50 (0.65)	Cracked	Cracked	Prone to cracking
7	Polymer-modified mortar	13.72(0.54)	Cracked severely in Arizona	Surface crazing in Florida and Illinois; cracked in Arizona	Prone to surface crazing; Cracked when exposed to low humidity and high temperature
8	Polymer-modified mortar	5.08 (0.20)	Cracked in Arizona	Fine surface crazing in Florida	Good crack resistance; Surface crazing attributed to finishing
9	Portland-cement concrete	8.64 (0.34)	Cracked in Arizona	Minor surface crazing in one Florida repair	Good crack resistance
10	Polymer-modified mortar	9.91 (0.39)	Cracked in Arizona	Surface and edge cracking	Prone to surface crazing and cracking
11	Cement-based mortar	6.10 (0.24)	Cracked in Arizona	No cracks	Good crack resistance
12	Polymer-modified portland-cement mortar	8.13 (0.32)	No cracks	Surface cracking in Illinois	Good crack resistance

Table 2
Summary of Laboratory Test Results

Material No.	Compressive Strength psi	Flexural Strength psi	28-day Tensile Strength psi	Coeff. of Thermal Expansion $x10^{-6}/°F$	Modulus of Elasticity psi x 10^6	Drying Shrinkage Millionths		Ring Test		German Angle Test (Cracks)	SPS Plate Test Max. tip deflection in.	Specific Creep @ 1-Year Millionths/psi	
						28-day	Peak	Implied Strain Millionths	Age of 1st Crack, days			Compressive	Tensile
1	6,610	289	451	5.8	2.8	178	366	667	6	None	0.0573	0.451	0.42
2	7,180	445	399	7.8	3.2	391	1,032	364	22	None	0.3282	0.603	0.831
3	6,360	421	513	7.1	3.7	479	1,116	685	17	None	0.3678	1.913	1.449
4	11,530	779	348	8.3	3.8	201	703	560	140	None	0.0792	0.260	0.609
5	9,830	758	93	7.8	4.5	258	690	840	10	None	0.0025	0.562	27.732
6	9,760	493	323	9.3	5.3	301	878	1,808	7	None	0.0610	0.872	0.608
7	4,330	365	467	8.5	2.7	1,779	2,682	3,414	4	None	1.4858	3.485	2.835
8	4,060	139	215	9.2	2.7	305	1,109	1,222	8	None	0.4283	1.894	3.587
9	4,780	415	323	6.9	2.5	429	877	955	23	None	0.3190	1.301	1.163
10	5,230	495	402	9.9	4.2	16	678	0	None	None	0.2063	2.037	0.072
11	9,620	503	390	7.6	5.9	339	641	810	15	None	0.2405	0.483	0.555
12	6,940	805	742	9.3	3.0	293	634	None	0	None	0.1560	1.157	0

Note: Divide psi by 145 to obtain MPa.
Multiply inches by 25.4 to obtain millimetres.
Multiply °F by 1.8 to obtain °C.

Table 3
Test Methods Used in the Project

Test	Reference	Comments
Laboratory		
Compressive	ASTM C 39 (ASTM 1994a)	76- by 152-mm (3- by 6-in.) cylinders. Three cylinders were tested for each material at 3, 7, and 28 days
Static modulus of elasticity	ASTM C 469 (ASTM 1994f)	76- by 152-mm (3- by 6-in.) cylinders
Flexural strength	ASTM C 78 (ASTM 1994b)	152- by 152- by 533-mm (6- by 6- by 21-in.) beams. Three beams were tested at 3, 7, and 28 days
Compressive dreep	ASTM C 512 (ASTM 1994g)	76- by 152-mm (3 by 6 in.). Nominal stresses 20 and 40% of compressive strength at 3, 7, and 28 days.
Coefficient of thermal expansion	ASTM C 531 (ASTm 1994h)	76- by 76- by 286-mm (3- by 3- by 11-1/4-in.) prisms
Drying shrinkage	ASTM C 157 (Modified) (ASTM 1994e)	76- by 76- by 286-mm (3- by 3- by 11-1/4-in.) prisms
Tensile strength	Nonstandard test. See Technical Report REMR-CS-57, p. 13 (Poston, Kesner, Emmons, and Vaysburd 1998)	76- by 76- by 305-mm (3- by 3- by 12-in.) specimens
Tensile creep	Nonstandard test. See Technical Report REMR-CS-57, p. 15 (Poston, Kesner, Emmons, and Vaysburd 1998)	76- by 76- by 305-mm (3- by 3- by 12-in.) specimens loaded to 20 and 40% of the tensile strength at 3, 7, and 28 days
Ring Test (sensitivity to cracking)	Nonstandard test. (See Standard Protocol for Material Data Sheet, Appendix A).	Geometry of the mold was specifically designed for this project
Field and Laboratory		
German Angle Test (sensitivity to cracking)	Nonstandard test. (See Standard Protocol for Material Data Sheet, Appendix A.)	German Ministry of Transport TP BE-PCC
SPS Plate Test (restrained volume change test)	Nonstandard test. See Technical Report REMR-CS-57, p. 13 (Poston, Kesner, Emmons, and Vaysburd 1998)	This test was specifically designed for this project

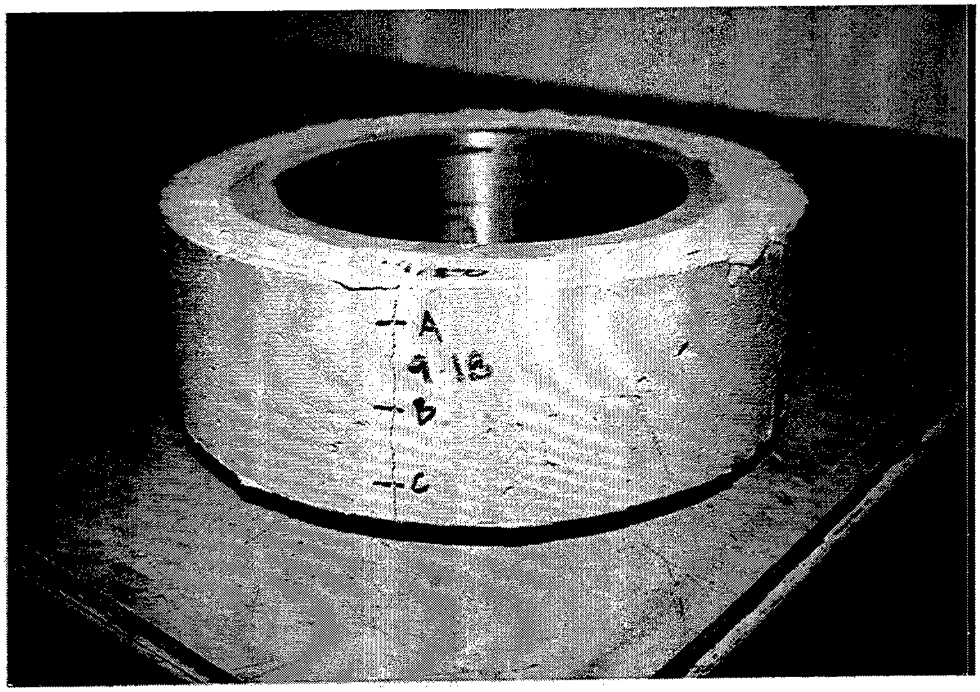


Figure 2. Ring Test (sensitivity to cracking)

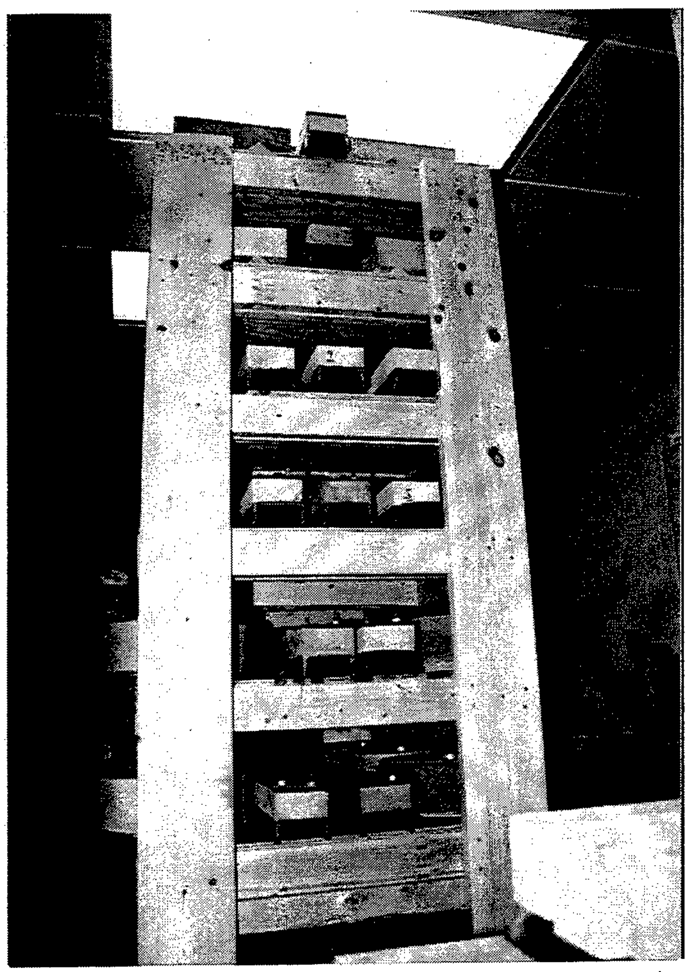


Figure 3. SPS Plate Test in the laboratory

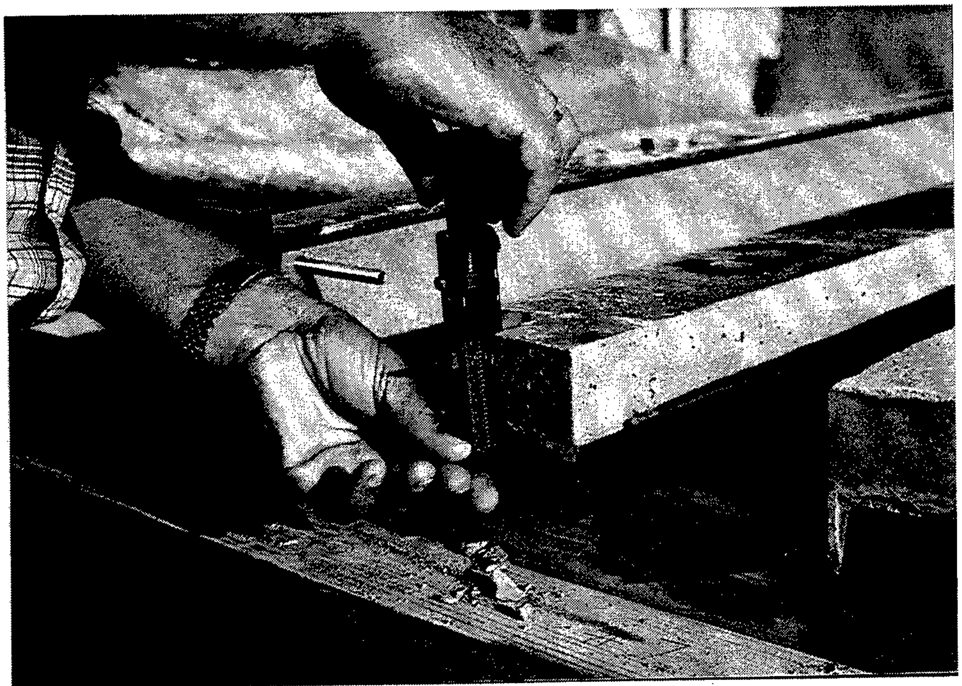


Figure 4. Measuring tip deflection of SPS Plate Test specimens in Arizona

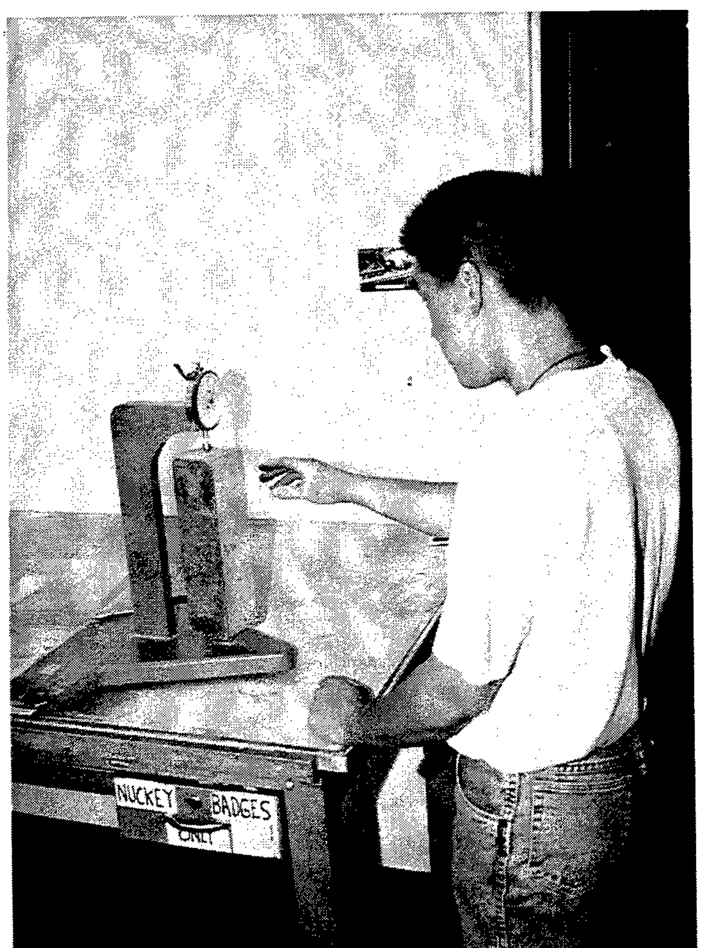


Figure 5. Drying shrinkage measurement (ASTM C 157 (1994e))

Tensile properties tests

Cracking in repairs is dependent on the interaction of the two competing processes: strength gain of the repair material on the one hand, and increase in restraining tensile stresses on the other hand. Interaction becomes effective immediately after material setting:

a. Shrinkage begins at the initial setting period in the already stiff restrained repair material, and therefore, tensile stresses are generated.

b. Tensile strength of the material being developed should be sufficiently high to accommodate tensile stresses, otherwise, cracking will occur.

The values of tensile strength vary widely depending on the test method used. Therefore, it is imperative to identify the test method used. Three kinds of tests have usually been used; the beam or modulus of rupture test, the split cylinder of Brazilian test, and the direct tension test. It was recognized that to determine basic tensile properties of repair materials such as tensile strength and tensile creep, a uniaxial tensile strength test is preferable to any other. Direct tension tests are complex to perform because of the difficulty of ensuring that the load is truly axial. In a ductile material, some eccentricity of load will have little effect on tensile strength. In a brittle material there is a relatively small amount of redistribution of stress, and consequently, the test gives an under estimate of tensile strength.

For purposes of this study, the test specimen with dimensions shown in Table 3 and special load frame were developed. It was decided to use long specimens with a reduced cross-sectional area away from the loading grips to obtain an adequately uniform stress field.

Time-dependent tensile deformations are of significant importance when the risk of cracking has to be considered. This arises, in practice, not only in design of repairs, but also in the design of water-retaining structures and in the estimation of the allowable tensile stresses in prestressed concrete structures. Tensile creep is considered important in repair materials because it allows for stress relaxation which reduces the potential for cracking.

Therefore at the present time, creep measurements in direct tension are more difficult than in compression, primarily because of the relatively low strength of material and hence the low stress levels that can be applied and the consequent low creep strains. It is normally assumed that the tensile creep is not significantly different from compressive creep, and, therefore, compressive creep property is used rather than of tensile creep property. It was decided that the tensile creep property is of significant practical importance, therefore, the measurement of this property shall be performed (Poston, Kesner, Emmons, and Vaysburd 1998).

Sensitivity to cracking tests

The amount of shrinkage depends on many factors, including the properties of the material, temperature, relative humidity of the environment, the absorptivity of the concrete substrate, the age when the repair is exposed to drying environment, and the geometry of the repair.

Laboratory unrestrained shrinkage tests alone may not offer sufficient information on the dimensional behavior of the repair, since virtually all repairs are restrained by boundary or by reinforcement and boundary. The study of the literature and practical experience demonstrates that there appears to be no clear-cut relation between restrained shrinkage and occurrence of cracking. Thus, restrained shrinkage tests were used to evaluate the restrained volume change cracking behavior of repair materials.

The methods commonly used for measuring restrained shrinkage cracking are described in the Phase I Report (Emmons and Vaysburd 1995). The purpose of the various restrained volume change tests adopted and developed in this study was to investigate the sensitivity to cracking. Field observations have shown that some materials crack much more readily than others under identical exposure conditions. Cracking resistance is undoubtedly compounded by a combination of several properties, and it was thought that the cracking tests made with a large number of materials might lead to the isolation of the effects of certain individual variables. According to the previous discussion, the determination of cracking resistivity of a material in a repair from shrinkage information recorded for a companion nonrestrained sample is very questionable. This emphasizes the importance of developing a method by which restrained volume changes induced stresses, and resulting cracking can be studied. To develop information regarding the cracking tendencies of repair materials, a comprehensive series of ring tests, using the basic procedures (Carlson and Reading 1988), were performed in the laboratory (Figure 2). The ring test adopted in this investigation provides a high and nearly constant restraint. Because of the axisymmetry, the geometry and boundaries do not significantly influence the results. The geometry of the ring test mold used was a modification to that described by Shah, Karagular, and Sarigaphuti (1992).

In addition to determining the number of days required to crack the material ring, periodically the width of the cracks that had formed were measured and recorded to evaluate the implied strain.

Two such test methods were used in the study, both in laboratory and in the field. The field samples were necessary to determine if the laboratory exposure specimens produced the same trend of results as the field specimens.

One of the restrained volume change methods used in the present study, SPS Plate test, is based on the system proposed by Emmons and Vaysburd (1995). The system is shown in Figures 3 and 4. As the material specimen expanded when exposed to rain, high humidity, and high temperature, or contracted during shrinkage and low temperature, the moving end of the specimen was reacting to all of these environmental factors. The movement of the free end was monitored periodically by a micrometer.

Another test, German Angle, was adopted from the Technical Test Regulations (TP BE-PCC) of the German Federal Ministry of Transport. The test is described in the Phase I program (Emmons and Vaysburd 1995). The German Angle test specimens were monitored under standard laboratory and field conditions for cracking. The time of cracking and the number of cracks were recorded.

Analysis of the Laboratory Test Results

The results of laboratory testing of 12 materials in the present program are summarized in Table 2. The test results for six cementitious and six polymer-modified materials are shown in Tables 4 and 5, respectively. A brief summary of the laboratory test results follows.

Strength properties

In accordance with the scope of work, the basic mechanical properties of selected repair materials were tested in the laboratory.

As a general observation, it can be concluded that the tested mechanical properties, compressive, direct tensile, and flexural strengths, revealed considerable differences among the repair materials tested in the present study.

Compressive strength. Results of compressive strength tests ranged from 28 to 80 MPa (4,060 to 11,530 psi) with an overall average of 50 MPa (7,186 psi).

Compressive strength for cementitious materials ranged from 33 to 80 MPa (4,180 to 11,530 psi) with an average of 57 MPa (8,258 psi); for polymer-modified materials – from 28 to 67 MPa (4,060 to 9,760 psi) with an average of 42 MPa (6,113 psi).

a. The lowest compressive strength (Material 8, 28 MPa (4,060 psi) was 20 percent less than that of regular concrete (Material 9, 33 MPa (4,780 psi)).

b. The highest compressive strength (Material 4, 80 MPa (11,530 psi)) was 140 percent higher than that of control concrete mixture (Material 9). The average compressive strength of polymer-modified materials (4.23 MPa (6,113 psi)) was only 75 percent that of cementitious materials (56.95 MPa (8,258 psi)).

c. Most of the repair materials tested in this study demonstrated significantly higher strength than average concrete substrate.

Table 4
Properties of Cementitious Materials

Material No.	Compressive Strength psi	Tensile Strength psi	Flexural Strength psi	Modulus of Elasticity psi x 10^6	Coefficient of Thermal Expansion $x10^{-6}/°F$	Drying Shrinkage millionths		Ring Test		SPS Plate Test Max. tip deflection, in.	Specific Creep @ 1 Year millionths/psi	
						28 days	Peak	Age of 1st Crack, days	Implied Strain millionths		Compressive	Tensile
1	6,610	451	289	2.8	5.8	178	366	6	667	0.0573	0.451	0.420
2	7,180	399	445	3.2	7.8	391	1,032	22	364	0.3282	0.603	0.831
4	11,530	348	779	3.8	8.3	201	703	140	560	0.0792	0.260	0.609
5	9,830	93	758	4.5	7.8	258	690	10	840	0.0025	0.562	27.732*
9	4,780	323	415	2.5	6.9	429	877	23	955	0.3190	1.301	1.163
11	9,620	390	503	5.9	7.6	339	641	15	810	0.2405	0.483	0.555
Average	8,258	334	457	3.78	7.37	299	718	-	699	0.1711	0.610	0.864

Note: Divide psi by 145 to obtain MPa.
Multiply inches by 25.4 to obtain millimetres.
Multiply °F by 1.8 to obtain °C.
* Not included in average.

Table 5
Properties of Polymer-modified Materials

Material No.	Compressive Strength psi	Tensile Strength psi	Flexural Strength psi	Modulus of Elasticity psi x 10^6	Coefficient of Thermal Expansion $x10^{-6}/°F$	Drying Shrinkage Millionths		Ring Test		SPS Plate Test	Specific Creep @ 1 Year Millionths/psi	
						28 days	Peak	Age of 1st Crack, days	Implied Strain Millionths	Max. tip deflection, in.	Compressive	Tensile
3	6,360	513	421	3.7	7.1	479	1,116	17	685	0.3678	1.913	1.449
6	9,760	323	493	5.3	9.3	301	878	7	1,808	0.0061	0.872	0.608
7	4.330	467	365	2.7	8.5	1,779	2,682	4	3,414	1.4858	3.485	2.835
8	4,060	215	139	2.7	9.2	305	1,109	8	1,222	0.4283	1.894	3.587
10	5,230	412	495	4.2	9.9	16*	678	None	0	0.2063	2.037	0.072
12	6,940	742	805	3.0	9.3	293	634	None	0	0.1560	1.157	0
Average	6,113	444	453	3.6	8.88	570	1,183	-	1,188	0.4417	1.893	1.4252

Note: Divide psi by 145 to obtain MPa.
Multiply inches by 25.4 to obtain millimetres.
Multiply °F by 1.8 to obtain °C.
* Not included in average.

Tensile strength. The results of the direct tensile strength tests ranged from 0.65 to 5.1 MPa (93 to 742 psi) with an overall average of 2.7 MPa (389 psi).

Tensile strength for cementitious materials ranged from 0.65 to 3.1 MPa (93 to 451 psi) with an average of 2.3 MPa (334 psi); for polymer-modified materials – from 1.5 to 5.1 MPa (215 to 742 psi) with an average of 3.1 MPa (444 psi).

The lowest value of tensile strength (Material 5, at 0.65 MPa (93 psi)), was 250 percent lower than that of regular concrete mixture (Material 9); the highest tensile strength (Material 12, at 5.1 MPa (742 psi)), was 130 percent higher than that of regular concrete mixture (Material 9). The average tensile strength of polymer-modified materials was 33 percent higher than regular concrete mixture (Material 9).

Two of the polymer-modified repair materials (Materials 6 and 8) and four of the cementitious repair materials (Materials 4, 5, 9, 11) did not satisfy the minimum requirements of the Preliminary Performance Criteria (Emmons and Vaysburd 1995). The tensile strength tested ranged from 1 percent (Material 5) to 11 percent (Material 12) from compressive strength of materials, with an average of 7 percent.

It should be noted that the results of the direct tensile strength tests were significantly lower than expected. This can be attributed to the difficulties of introduction of pure axial load along with various other factors.

Flexural strength. The results of flexural strength (modulus of rupture) tests ranged from 1.0 to 5.6 MPa (139 to 805 psi) with an overall average of 3.1 MPa (455 psi).

The flexural strength of cementitious materials ranged from 2.0 to 5.4 MPa (289 to 779 psi) with an average of 3.2 MPa (451 psi); for polymer-modified materials from 1.0 to 5.46 MPa (139 to 805 psi) with an average of 3.1 MPa (453 psi). The average flexural strength of both polymer-modified and cementitious materials was 40 percent higher than control concrete mixture (Material 9).

The ratio of flexural to direct tensile strength for materials tested varies from 0.64 to 8.15, with the ratio of the overall averages 1.17. These ratios are very unusual for cement-based materials. Flexural tests usually give results which are substantially higher than direct tension tests. This test tends to overestimate the direct tensile strength by about 50 percent, largely due to the fact that the simple flexure formula assumes that the stress varies linearly across the cross section of the beam specimen. But because cement-based materials have a nonlinear stress-strain curve, this assumption is not true.

As already indicated, the results obtained in direct tensile strength tests are viewed with skepticism. Consequently, flexural (modulus of rupture) is recommended for use in performance criteria.

Modulus of elasticity

Values for modulus of elasticity tested ranged from 17×10^3 to 41×10^3 MPa (2.5×10^6 to 5.9×10^6 psi) with an overall average of 25.5×10^3 MPa (3.7×10^6 psi) which is about maximum requirement proposed in the preliminary performance criteria.

The average modulus of elasticity for cement-based materials was 106 percent of that of polymer-modified materials. Polymer-modified Materials 6 and 10 and cementitious Materials 4, 5, and 11 exceeded the preliminary performance requirement for modulus of elasticity.

Thermal properties

One of the factors affecting dimensional compatibility of a repair material with existing concrete substrate, coefficient of thermal expansion, was evaluated.

The study demonstrated that the coefficient of thermal expansion varies significantly among the cementitious materials as well as the polymer-modified materials. For the cementitious materials, the range was between −19 percent to +20 percent. When compared to control concrete mixture (Material 9), the polymer-modified materials had a much higher range of variation between +3 percent and +43 percent.

The coefficient of thermal expansion, long regarded an important and often critical feature of polymer-based repair materials only, may also be an important variable in cementitious and polymer-modified materials. It was shown that the thermal expansion of some materials is as much as 43 percent (Material 10) higher than that of the control concrete mixture (Material 9).

It is interesting to note that the belief in the irrelevance of the coefficient of thermal expansion as compatibility property for cementitious and polymer-modified cementitious materials has gained such widespread acceptance that most workers on the subject do not even question this issue. The marked differences in thermal coefficient of expansion between some of the repair materials and concrete must also be considered in terms of composite performance – compatibility. As with other volume change effects, the difference may, or may not, be relevant depending upon the particular situation.

Time-dependent deformations

The time-dependent deformations affecting the dimensional compatibility are drying shrinkage and creep.

Drying shrinkage. It was found that the variation in drying shrinkage, the most critical material property controlling dimensional compatibility and resulting resistance to cracking, was very significant among cementitious and polymer-modified cementitious materials. Drying shrinkage for polymer-modified materials varied between 16 and 1,779 millionths at 28 days, and between 634 and 2,682 millionths at 18 months (peak).

Drying shrinkage for cementitious materials varied between 178 and 429 millionths at 28 days and 366 and 1,032 millionths at maximum.

The average shrinkage at 28 days was: for polymer-modified materials, 570 millionths; for cementitious materials, 299 millionths. The average maximum shrinkage at for these materials was 1,183 and 718 millionths, respectively.

With the exception of Material 7, shrinkage results after 28 days of drying were lower than expected. Also, the variation in this property was much less than was anticipated during the material selection process based on information provided by the manufacturers. Nine of the twelve materials met the preliminary performance criteria of 400 millionths drying shrinkage at 28 days.

Analysis of drying shrinkage test results at 28 days and peak suggest that early-age shrinkage are not always adequate for reliable selection of repair materials. Values beyond the 28 days are necessary to adequately address long-term drying shrinkage of 76- × 76- × 286-mm (3- × 3- × 11¼-in.) test specimens at 50 percent RH. For example, Materials 4, 10, and 12 exhibited about the same ultimate shrinkage values; however, their 28-day shrinkage ranged from 16 to almost 300 millionths.

Overall, the ratios of peak shrinkage values to 28–day values ranged from 1.5 to 3.6 (excluding Material 10) with an average ratio of 2.49 (cementitious – 2.58, polymer-modified – 2.41). This indicates that cementitious and polymer-modified materials were found to shrink at almost the same rate from 28-day ages to peak. Based on the results presented in Table 6, the average 28-day shrinkage was about 45 percent of peak. Measurement of drying shrinkage is shown in Figure 5.

Table 6
Relationship between 28-day and Peak Shrinkage

Cementitious Materials		Polymer-modified Materials	
Material No.	28-day Shrinkage / Ultimate Shrinkage Ratio	Material No.	28-day Shrinkage / Ultimate Shrinkage Ratio
1	0.49	3	0.43
2	0.38	6	0.34
4	0.29	7	0.66
5	0.37	8	0.28
9	0.49	10	-
11	0.53	12	0.46
Average	0.43	-	0.43

Compressive and tensile creep. Values of specific compressive creep at 1-year age varied widely between 37.7 and 506 millionths/MPa (0.26 and 3.49 millionths/psi) with an overall average of 181 millionths/MPa

(1.25 millionths/psi). The average specific compressive creep of polymer-modified repair materials was about three times higher than that of cementitious materials.

Values of specific tensile creep at 1-year age varied between 10.4 and 4,021 millionths/MPa (0.072 and 27.732 millionths/psi) with overall average of 481 millionths/MPa (3.32 millionths/psi). The average specific tensile creep of polymer-modified repair materials was 260 percent less than that of cementitious materials.

If Materials 5, 10, and 12 are excluded from the comparison, the rest of the data suggest a modest correlation between specific tensile and compressive creep with the value of creep in tension averaging about 1.2 times that of compression at the age of 1 year.

If Material 5 is excluded, which in many respects manifested very unusual behavior during testing, the average specific tensile creep of polymer-modified repair materials is two times higher than that of cementitious materials.

The importance of creep and creep relaxation properties for tensile strain capacity and crack resistance of repair materials has been widely recognized. The experience of this study clearly demonstrate that to determine basic tensile properties of cement-based materials, including direct tensile strength and tensile creep, a uniaxial test is necessary, but it has proven difficult to develop a test system which is relatively simple, economic, and truly uniaxial.

Sensitivity to cracking

Laboratory tests. Two parameters were measured in the ring test: when the cracks first appeared in the material ring and implied strain associated with the measured crack widths at the age of approximately 18 months. The implied strain was determined by dividing the total crack width by the ring circumference. The cracks never formed in the test specimens for Materials 10 and 12. Material 4 cracked at the age of 140 days. For the remainder of materials, the age of first crack varied from 4 to 23 days. The average crack width at 18-month age varied widely from 0 to 3.4 mm (0 to 0.14 in.) with an overall average of 0.91 mm (0.04 in.). The average implied strain varied from 0 to 3,414 millionths. The average implied strain of polymer-modified materials was 1.7 times higher than that of cementitious materials.

No cracking was observed in the German Angle Test under controlled laboratory conditions over the 18-month test period. Thus, the results from this test provided no information with regard to the materials' sensitivity to cracking in the laboratory.

The data from the SPS Plate Test indicate a relatively large increase in tip deflection at the early ages, in the first 28 days, followed by a relatively modest increase in deflection over the remaining 18 months. The tip deflections varied substantially from as low as 0.06 mm (0.0025 in.) to as high as 37.7 mm

(1.49 in.). The polymer-modified repair materials had a tip deflection about 2.5 times larger than that of cementitious materials. The results of this test reasonably correlate with the results of the ring test. The two materials (No. 10 and 12) which did not crack in the ring test are among the materials having lowest tip deflection. Material No. 7, with the earliest crack formation and highest implied strain, also had the largest tip deflection, about five times that of the next highest measured deflection.

Field tests. Field testing was carried out in three areas located in South Florida (Boca Raton), Illinois (Chicago), and Arizona (Phoenix). Experimental repairs testing sites are shown in Figures 6, 7, and 8. These sites were selected to provide a wide variation in exposure conditions. The program included installation of 12 repair materials in three each prefabricated concrete slabs at each test site (Figures 9, 10, 11) and monitoring them for an 18-month period following the installation. In addition to the experimental repair testing, the German Angle and SPS Plate crack sensitivity tests were performed. These field specimen tests were

Figure 6. Material mixing at the South Florida testing site

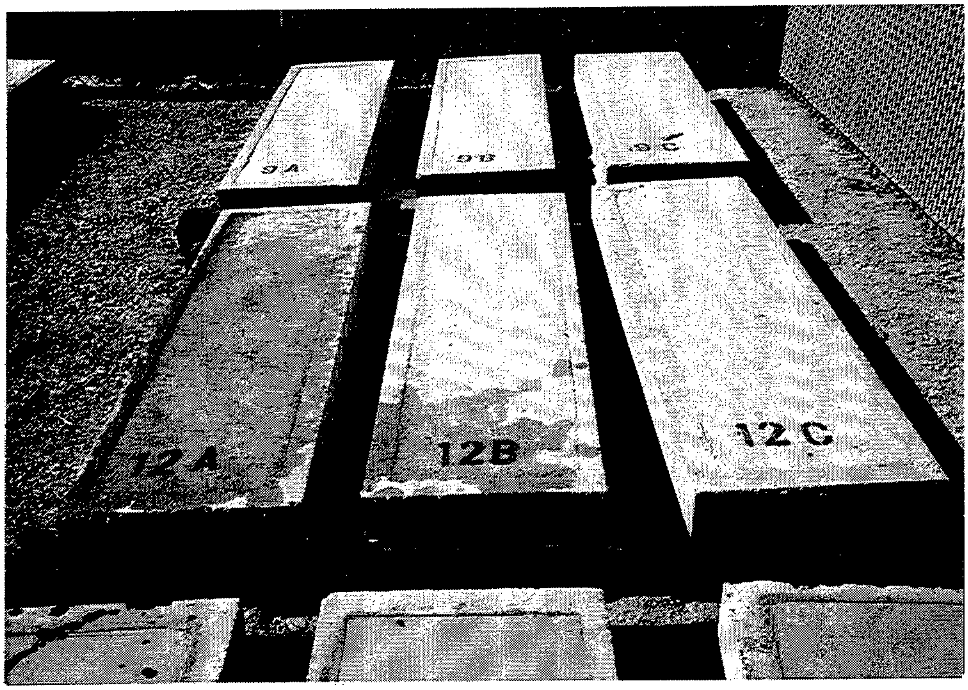


Figure 7. Experimental repair slabs in Illinois


Figure 8. A view of the testing site in Arizona

Figure 9. Experimental repair finishing

Figure 10. Two experimental repairs completed

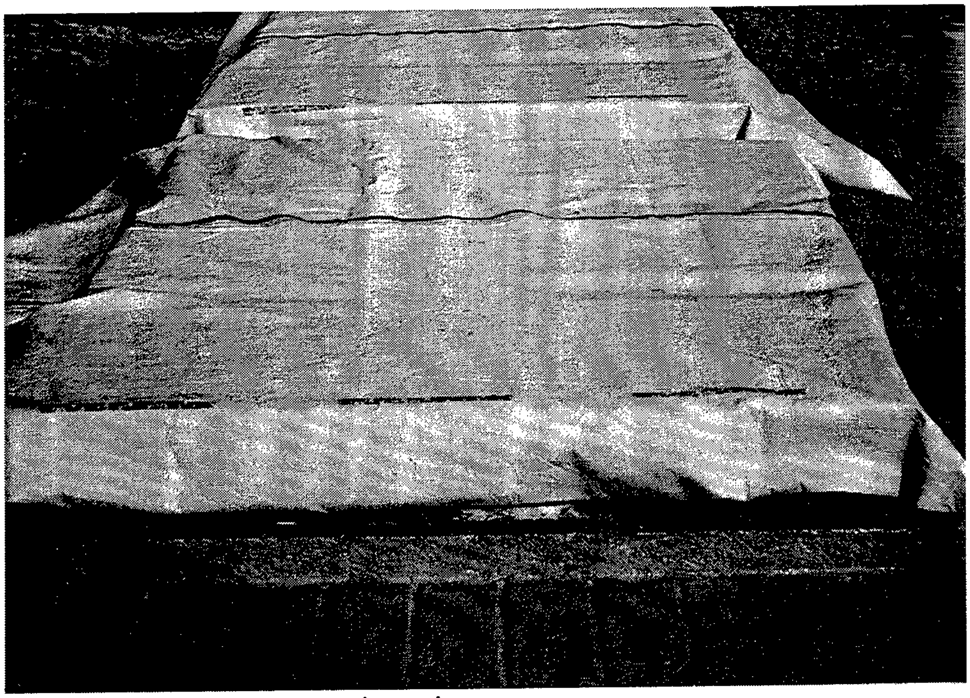


Figure 11. Experimental repairs curing

essentially the same as those in the laboratory program. The reason for performing these tests under the in situ conditions is that the experimental results obtained in a laboratory may represent, and often do, a better situation than can be expected in the field, because in situ swings in temperature and humidity are not represented in these or any other laboratory tests.

Detailed methodologies and results of each field test are not included in this report. The summary of field test results is presented in Table 1.

The following conclusions relevant for developing performance criteria can be made based on a comprehensive review of the results of the field test program.

a. The various repair materials exhibited substantial differences in dimensional behavior and sensitivity to cracking in experimental repairs and specimen testing. Only six materials (50 percent) tested demonstrated satisfactory performance in experimental repairs, regardless of variations in service conditions within the environmental ranges studied. These are Materials 1, 4, 8, 9, 11, and 12.

b. The performance of the remaining materials was rated below that of the control concrete mixture (Material 9).

c. Two materials, 2 and 3, were susceptible to cracking only when subjected to high temperature and low humidity conditions and their overall performance can be rated as marginal. The remaining four materials (5, 6, 7, and 10) exhibited a tendency to cracking regardless of exposure conditions and their overall performance can be rated as unsatisfactory.

Examples of the three materials sensitivity to cracking are in Figures 12, 13, 14, and 15.

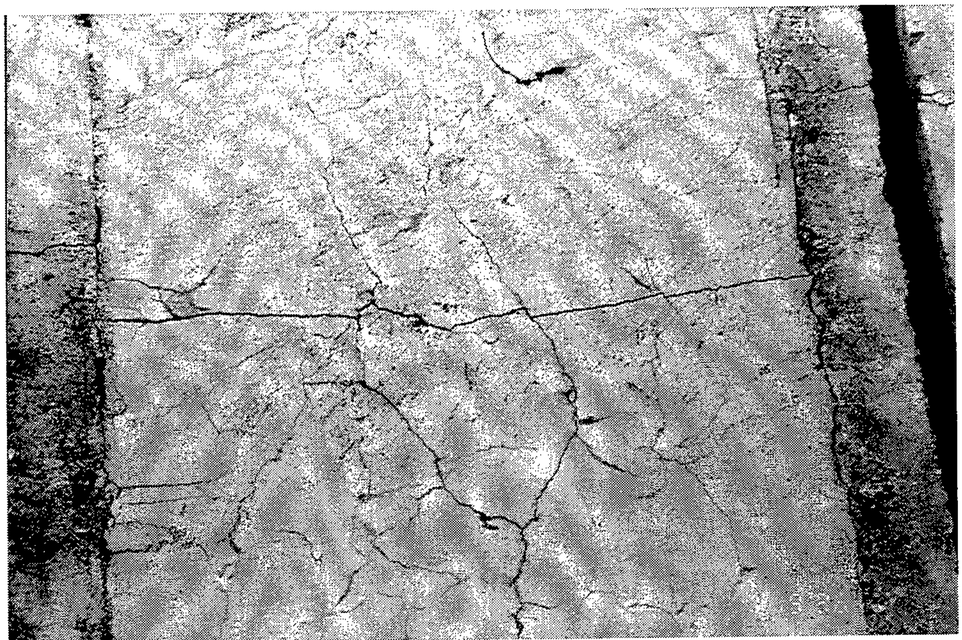


Figure 12. Cracks in experimental repair Slab 5B (Florida)

Figure 13. Surface crazing of experimental repair Slab 7A in Illinois

Figure 14. Cracks in experimental repair Slab 7C in Arizona

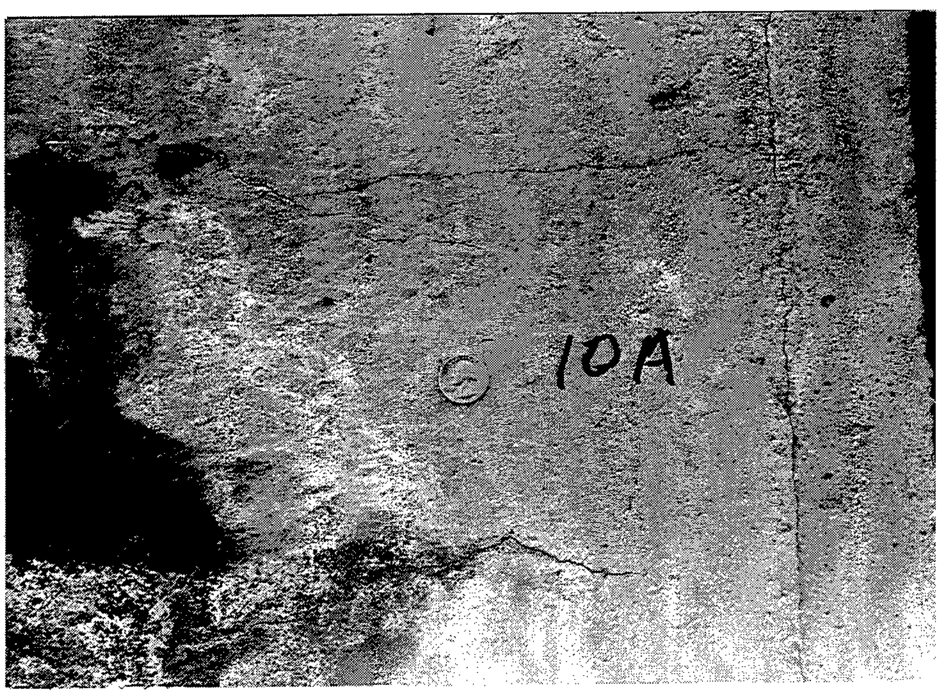


Figure 15. Cracks in experimental repair Slab 10A in Arizona

d. In the SPS Plate Test, the eight best materials exhibited maximum deflections ranging from 4.3 to 5.8 mm (0.17 to 0.23 in.) with an average of 5.1 mm (0.20 in.). With one exception (Material 5), the remaining materials exhibited maximum deflections ranging from 6.9 to 10.4 mm (0.27 to 0.41 in.) with an average of 8.9 mm (0.35 in.), approximately 50 percent higher than the eight best materials. Only Material 5 exhibited poor crack resistance in the experimental repairs. The results of the field study indicate that the SPS Plate Test results correlate reasonably well with the cracking behavior of field repairs. SPS Plate Test specimens are shown in Figures 16 and 17.

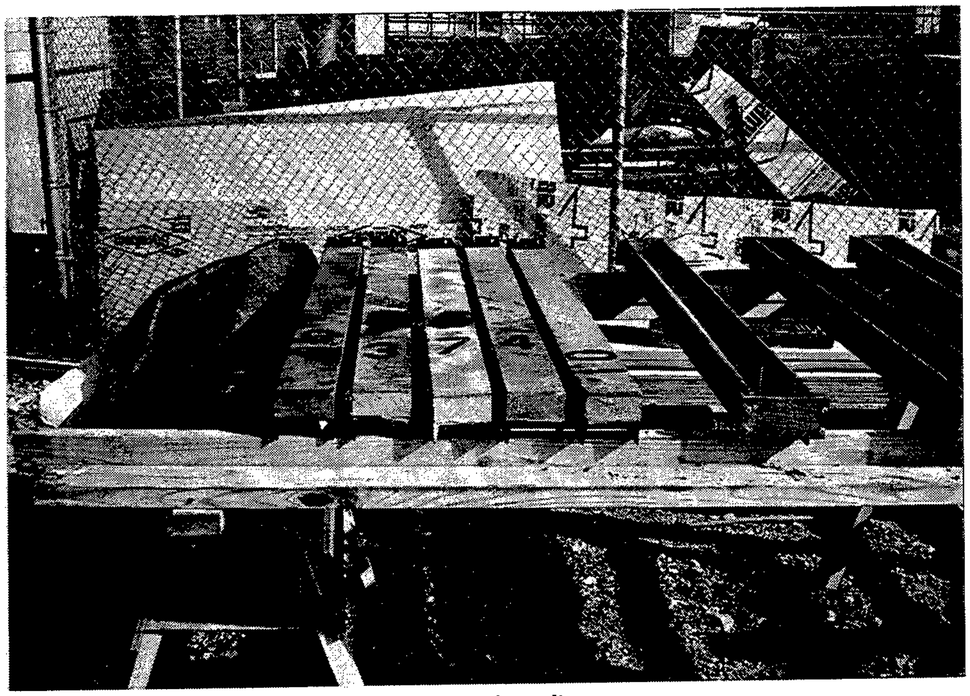


Figure 16. SPS Plate Test at Illinois testing site

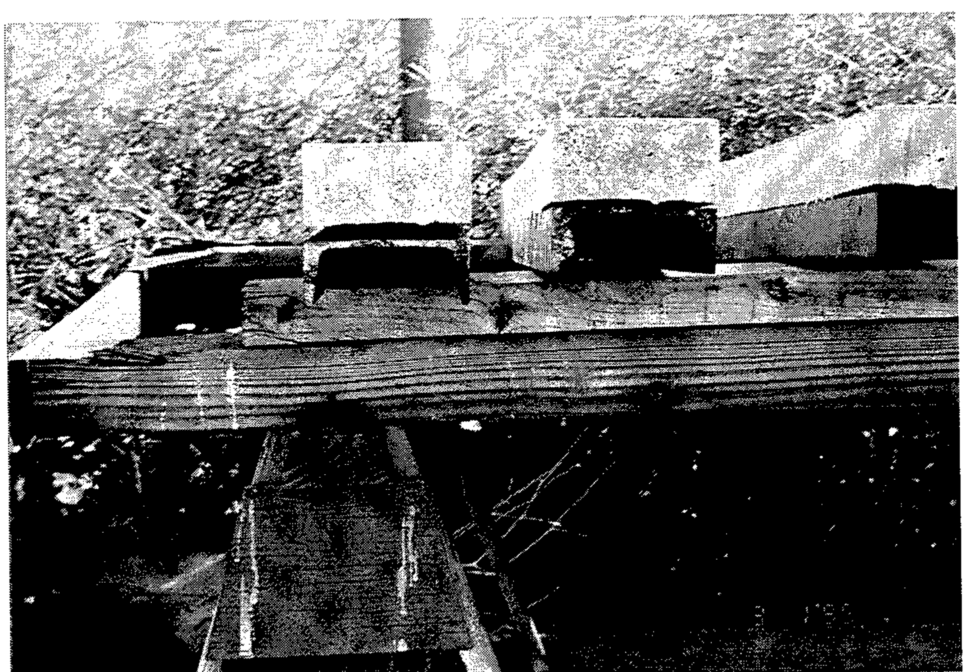


Figure 17. SPS Plate Test. Specimen tip deflections

e. Four materials (1, 2, 4, and 12) did not exhibit cracking in German Angle Test, and three of these materials, No. 1, 4, and 12, were among the six best materials. Material 2 was among two materials with the marginal rating. The four materials (5, 6, 7, and 10) with unsatisfactory performance in the experimental repairs also experienced cracking in the German Angle Test. The results indicate that this test correlates well with actual field performance of experimental repairs. The German Angle Test is illustrated in Figures 18, 19, and 20.

f. It was noticed that in several cases, three repairs with the same material at a given test site manifested different cracking behavior. These variations in performance are attributed, at least in part, to field operations. It was obvious from the field study that a substantial factor in performance of repair materials in-place critically depends upon mixture proportioning and construction operations, consolidation, finishing, and curing, in particular.

Figure 18. German Angle Test. Placing the material mixture in the mold

Figure 19. German Angle Test. Specimens after completion of curing in Chicago

Figure 20. German Angle Test. Specimens after 18 months exposure

3 Correlation of Test Results with Field Performance

General

The objective of this study, as indicated earlier, is to develop a reliable method for predicting the ultimate dimensional performance of repair materials from the results of relatively short-term tests on small specimens. This task is complicated by the fact that any material tested in the laboratory is not identical to that tested in the field due to many causes. Also, forces exerted by nature are different in type, duration, and magnitude.

Materials Ranking

For the purposes of developing performance criteria, an attempt was made in analysis of field performance to rank the various materials based on monitoring the experimental repairs for cracking and also monitoring the German Angle and SPS Plate Field Tests (Emmons, Vaysburd, Poston, and McDonald 1998). The materials were ranked relative to each other, with 1 being the best performance and 12 being the poorest, and summarized in Table 7.

For comparison, the ranking of laboratory results was performed. The rankings of the repair materials based on the results of various tests and overall laboratory performance are presented in Table 8. Overall ranking of repair materials is based simply on the summation of all ranks in the individual tests. On this basis, materials with low scores should be more resistant to cracking. The comparison of overall laboratory performance of materials with field performance of experimental repairs is shown in Figure 21.

Considerable study has been given to the data shown in these tables and figure as well as the material properties determined in the laboratory and material performance exhibited in the experimental repairs. In spite of substantial differences between field performance of repairs and laboratory testing of individual repair materials, there is an apparent relationship between the overall laboratory and field performances (Table 9). Nine materials, 75 percent, received similar rankings in both studies.

Table 7
Relative Ranking of Materials in the Field Study

Material No.	Dimensional Stability Cracking	German Angle Test	SPS Plate Test
4	1-3	1-4	3
11	1-3	5-7	4
1	1-3	1-4	5-6
12	4	1-4	7
8	5-6	5-7	2
9	5-6	5-7	8
2	8	1-4	5-6
3	7	10	10
10	9	8	9
7	10	9	11
5	12	11	1
6	11	12	12

Table 8
Ranking of Materials in the Laboratory Tests

Overall Rank	Material No.	Compressive Strength (a)[1]	Tensile Strength (b)[2]	Flexural Strength (b)[2]	Modulus of Elasticity (a)[1]	Coeff. Of Thermal Expansion (a)[1]	Shrinkage (a)[1]		Ring Test		SPS Plate Test (a)[1]	Specific Compressive Creep (b)[2]	Specific Tensile Creep (b)[2]
							28 days	Peak	Age f 1st Crack (a)[1]	Implied Strain (a)[1]			
1	12	7	1	1	5	10-11	5	2	1-2	1-2	5	7	12
2	10	4	5	5	9	12	1	4	1-2	1-2	6	3	11
3	1	6	4	11	4	1	2	1	11	5	2	11	10
4	9	3	9-10	8	1	2	10	7	4	9	8	6	5
5	4	12	8	2	8	7	3	6	3	4	4	12	8
6-8	3	5	2	9	7	3	11	11	6	6	10	4	4
6-8	5	11	12	3	10	5-6	4	5	8	8	1	10	1
6-8	11	9	7	4	12	4	8	3	7	7	7	1	9
9	2	8	6	7	6	5-6	9	9	5	3	9	9	6
10	8	1	11	12	2-3	9	7	10	9	10	11	5	2
11	7	2	3	10	2-3	8	12	12	12	12	12	2	3
12	6	10	9-10	6	11	10-11	6	8	10	11	3	8	6

[1] a. 1 (Low) – 12 (High)
[2] b. 1 (High) – 12 (Low)

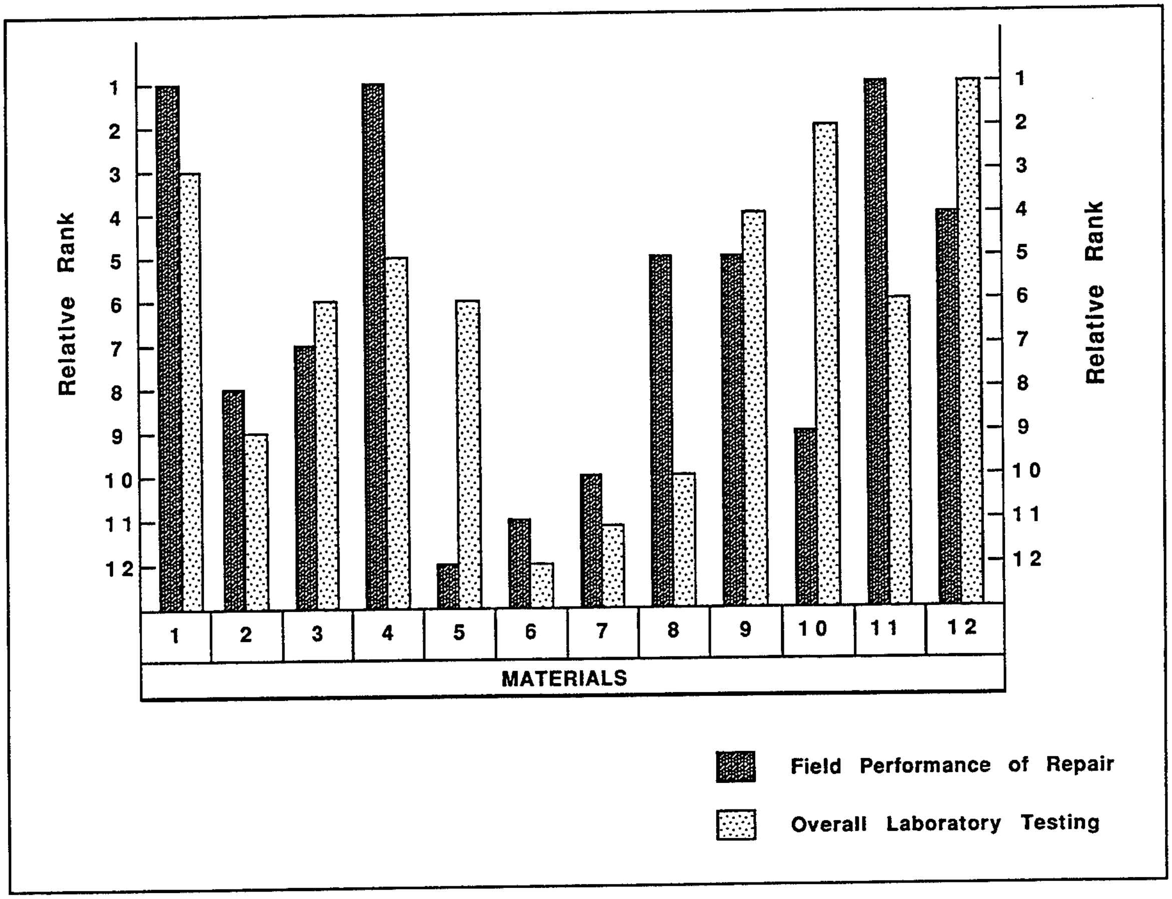


Figure 21. Comparison of material ranks in field performance and laboratory testing

Table 9
Comparison of Material Performance in Field Repairs and Laboratory Tests[1]

Material No.	Relative Rank: Experimental Repairs	Relative Rank: Laboratory
1	1-3	3
2	8	9
3	7	6-8
4	1-3	5
5	12	6-8
6	11	12
7	10	11
8	5-6	10
9	5-6	4
10	9	2
11	1-3	6-8
12	4	1

[1] Correlation is based on whether material is placed in experimental repair and laboratory tests in the group of six satisfactory performances or in the group of six remaining materials. Shading indicates absence of correlation.

Correlation of Laboratory and Field Data

Results of the laboratory and field investigations were correlated in an attempt to evaluate how individual material properties, or combinations of properties, affect the potential for cracking of field repairs. For the purposes of this correlation, materials are combined in three groups based on their rankings in field performance tests: six materials performed satisfactorily, two materials exhibited marginal performance, and four materials performed unsatisfactorily (Table 10). It should be noted that the numerical material order (rank) in each of the groups is, to a certain degree, subjective and should not be over-interpreted. Nonetheless, they confirm the general observations of the present study.

Strength

It is generally agreed that the potential for cracking of cement-based repair materials increases with high compressive strengths, despite inherently higher tensile strengths. Increased cracking is usually attributed to the typically higher modulus of elasticity, lower creep, and possibly higher shrinkage of high-strength materials. However, the results of this study indicate that, for the range of materials tested, there was no significant correlation between compressive strength and dimensional stability of the field repairs (Figure 22). Therefore, a requirement for compressive strength was not included in the performance criteria for nonstructural or protective repairs, which are the primary focus of this study.

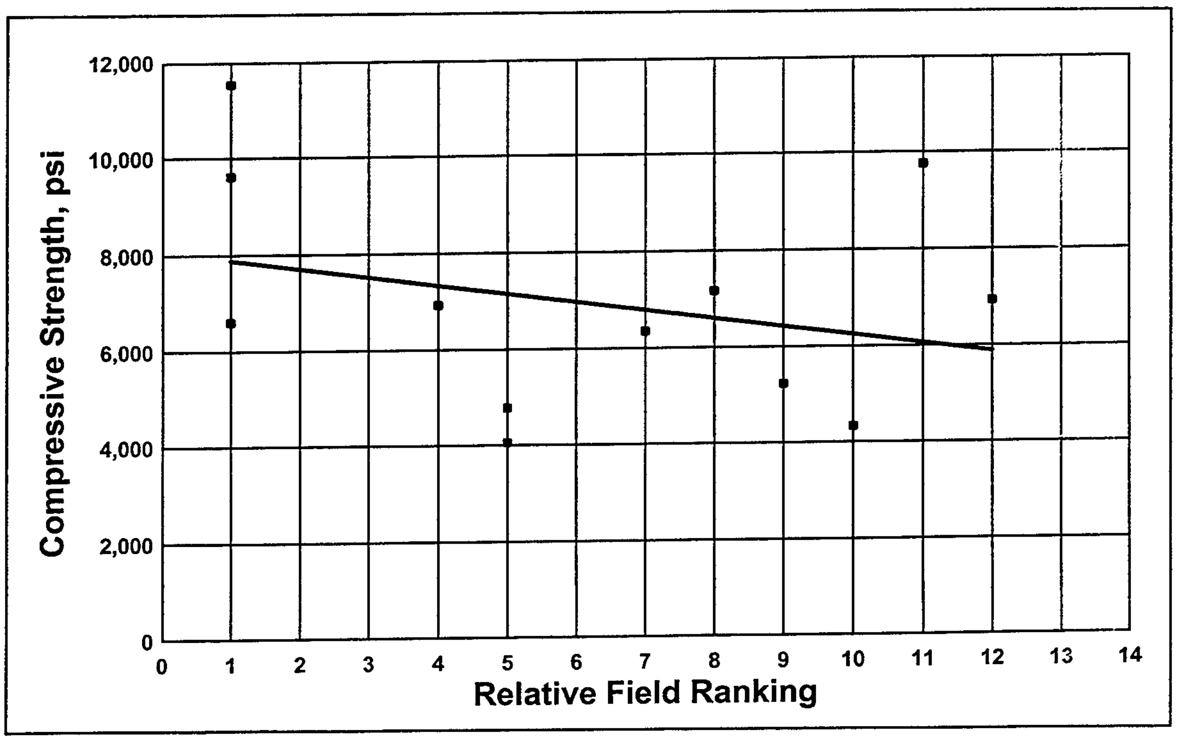


Figure 22. Correlation between compressive strength and field performance (divide psi by 145 to obtain MPa)

Table 10
Summary of Field and Laboratory Test Results

Field Perf. Rank	Material No.	Field Tests Results: German Angle	Field Tests Results: SPS Plate Test in.	Laboratory Tests Results: Compressive Strength psi	Tensile Strength psi	Flexural Strength psi	Modulus of Elasticity psi x 10^6	Coeff. Of Thermal Expansion x 10^{-6}/°F	Drying Shrinkage Millionths: 28 days	Drying Shrinkage Millionths: Peak	Ring Test: Age of 1st Crack days	Ring Test: Implied Strain Millionths	German Angle	SPS Plate Test in.	Specific Creep @ 1 year Millionths/psi: Compressive	Specific Creep @ 1 year Millionths/psi: Tensile
Group 1 - Satisfactory Performance Materials																
1-3	1	No crack	0.26	6,610	451	289	2.8	5.8	178	366	6	667	No crack	0.06	0.451	0.420
1-3	4	No crack	0.21	11,530	348	779	3.8	8.3	201	703	140	560	No crack	0.08	0.260	0.609
1-3	11	Crack in AZ	0.24	9,620	390	503	5.9	7.6	339	641	15	810	No crack	0.24	0.483	0.555
4	12	No crack	0.32	6,940	742	805	3.0	9.3	293	634	None	0	No crack	0.16	1.157	0
5-6	8	Crack in AZ	0.20	4,060	215	139	2.7	9.2	305	1,109	8	1,222	No crack	0.43	1.894	3.587
5-6	9	Crack in AZ	0.34	4,780	323	415	2.7	6.9	429	877	23	955	No crack	0.32	1.301	1.163
Average			0.26	7,260	412	488	3.5	7.8	291	722		701		0.22	0.924	1.287
Group 2 - Marginal Performance Materials																
7	3	Crack in AZ	0.43	6,360	513	421	3.7	7.1	479	1,116	17	685	No crack	0.37	1.913	1.449
8	2	No crack	0.26	7,180	399	445	3.2	7.8	391	1,032	22	364	No crack	0.33	0.603	0.831
Average			0.35	6,770	456	433	3.45	7.4	435	1,074		525		0.35	1.258	1.140
Group 3 – Unsatisfactory Performance Materials																
9	10	Crack in AZ	0.39	5,230	402	495	4.2	9.9	16	678	None	0	No crack	0.21	2.037	0.072
10	7	Crack in AZ	0.54	4,330	467	365	2.7	8.5	1,779	2,682	4	3,414	No crack	1.49	3.485	2.835
11	6	Cracked	0.65	9,760	323	493	5.3	9.3	301	878	7	1,808	No crack	0.06	0.872	0.608
12	5	Cracked	0.13	6,940	93	758	4.5	7.8	258	690	10	840	No crack	0	0.562	27.73
Average			0.43	6,560	321	528	4.2	8.9	588	1,232		1,516		0.44	1.739	7.81

Note: Divide psi by 145 to obtain MPa;multiply inches by 25.4 to obtain millimetres; multiply °F by 1.8 to obtain °C.

Overall, there was no significant correlation between direct tensile strength and field performance of repair materials, although the trend was for improved field performance with increased tensile strength (Figure 23a). However, there was a significant correlation between tensile strength and field performance for those materials that exhibited marginal and unsatisfactory performance (Figure 23b). It should be noted that 10 of the 12 materials exhibited tensile strengths in excess of 2.1 MPa (300 psi) and 75 percent of the materials exhibited strengths within a range of approximately 2.1 to 3.4 MPa (300 to 500 psi). The proposed performance criteria requires a minimum direct tensile strength of 2.8 MPa (400 psi).

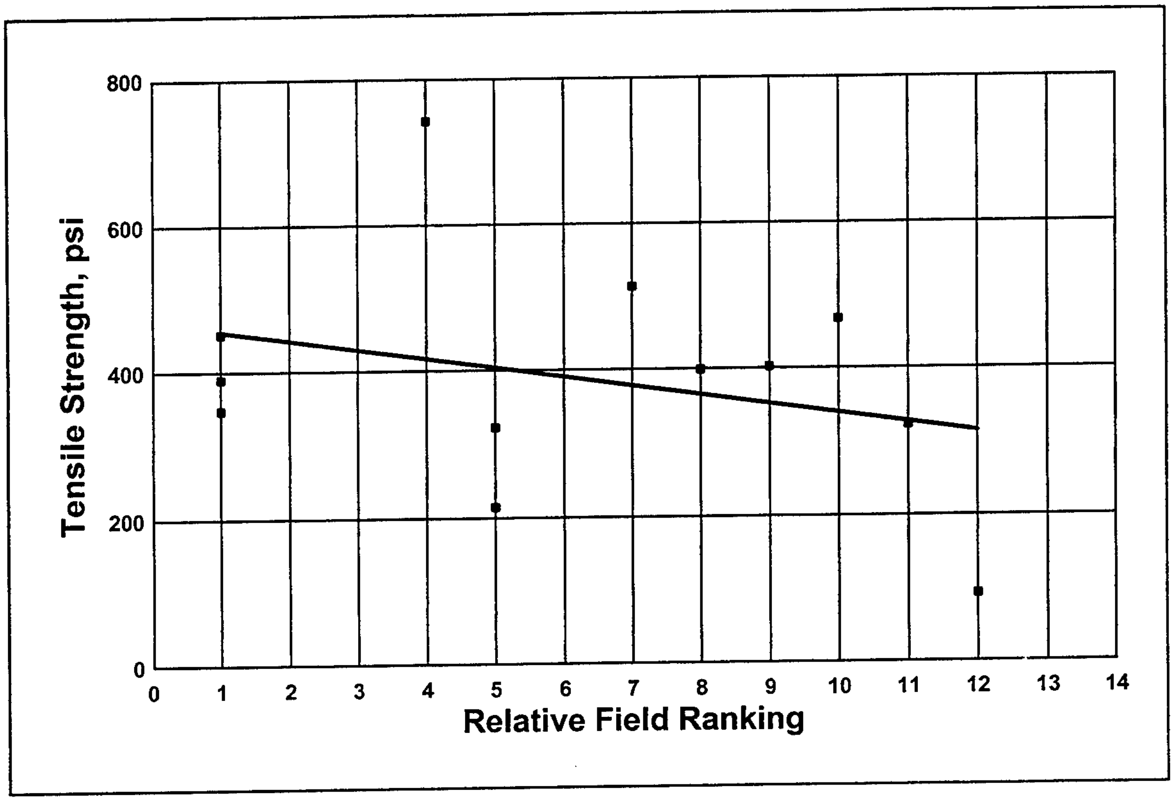
The results of this study indicate that there was no correlation between flexural strength and field performance; in fact, there was no apparent trend between flexural strength and field performance (Figure 24).

Modulus of elasticity

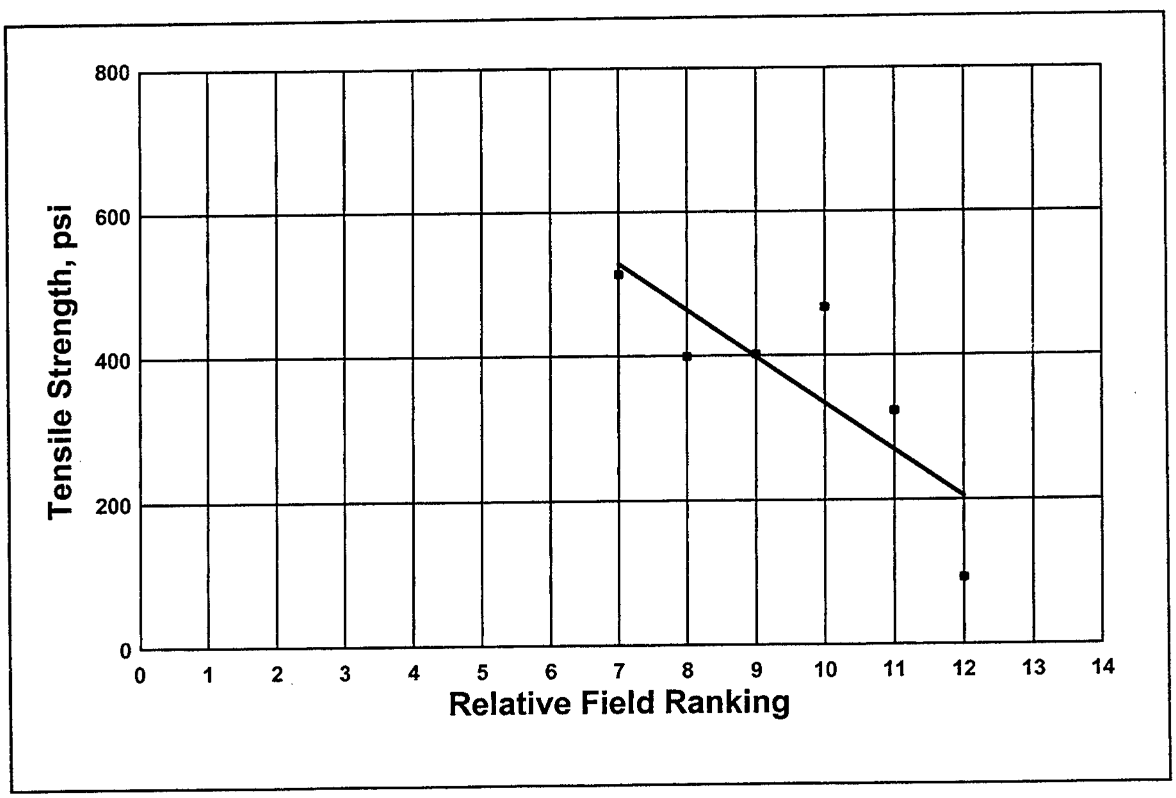
It is generally agreed that the potential for cracking of cement-based repair materials decreases with decreases in modulus of elasticity because of its effect on the magnitude of stresses induced by drying shrinkage and stress relaxation through creep. However, the overall results of this study indicate that, for the range of materials tested, there was no significant correlation between modulus of elasticity and field performance. It should be noted that 10 of the 12 materials exhibited moduli within a relatively narrow range of approximately 19 to 31 GPa (2.7 to 4.5 $\times$ 10^6 psi). Excluding Material 11, which exhibited a significantly higher modulus of elasticity compared to the other materials with acceptable field performance, there was a modest correlation between modulus of elasticity and field performance (Figure 25). Even though this correlation is below expectations, it would seem reasonable to state that this material property is very important, but its importance lies in its effect on other material properties, such as shrinkage and creep. The proposed performance criteria limits modulus of elasticity to a maximum value of 24 GPa (3.5 $\times$ 10^6 psi).

Thermal expansion

Overall, there was no significant correlation between coefficient of thermal expansion and field performance. However, the trend was for improvement in field performance with decreasing coefficients of thermal expansion (Figure 26). The materials that exhibited unsatisfactory field performance had an average coefficient of expansion of 16 millionths/deg C (8.9 millionths/deg F). In comparison, the coefficient of thermal expansion of the remaining materials averaged 14 millionths/deg C (7.8 millionths/deg F). Contrasting results of laboratory and field tests on Material 10 illustrate the importance of this material property. This material ranked third overall in laboratory test results but exhibited unsatisfactory resistance to cracking in the field tests. The material's relatively poor field performance is attributed to its high coefficient of thermal expansion



a. Overall



b. Marginal and unsatisfactory material

Figure 23. Corrrelation between tensile strength and field performance (divide psi by 145 to obtain MPa)

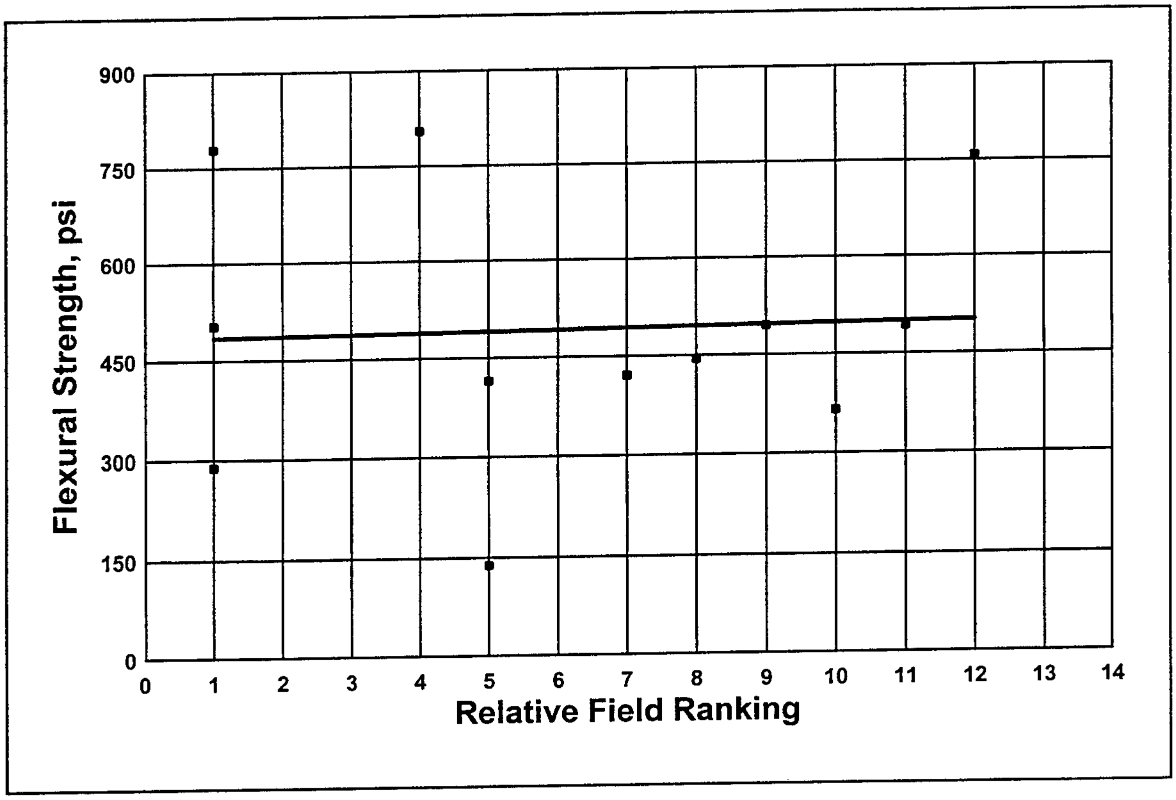


Figure 24. Correlation between flexural strength and field performance (divide psi by 145 to obtain MPa)

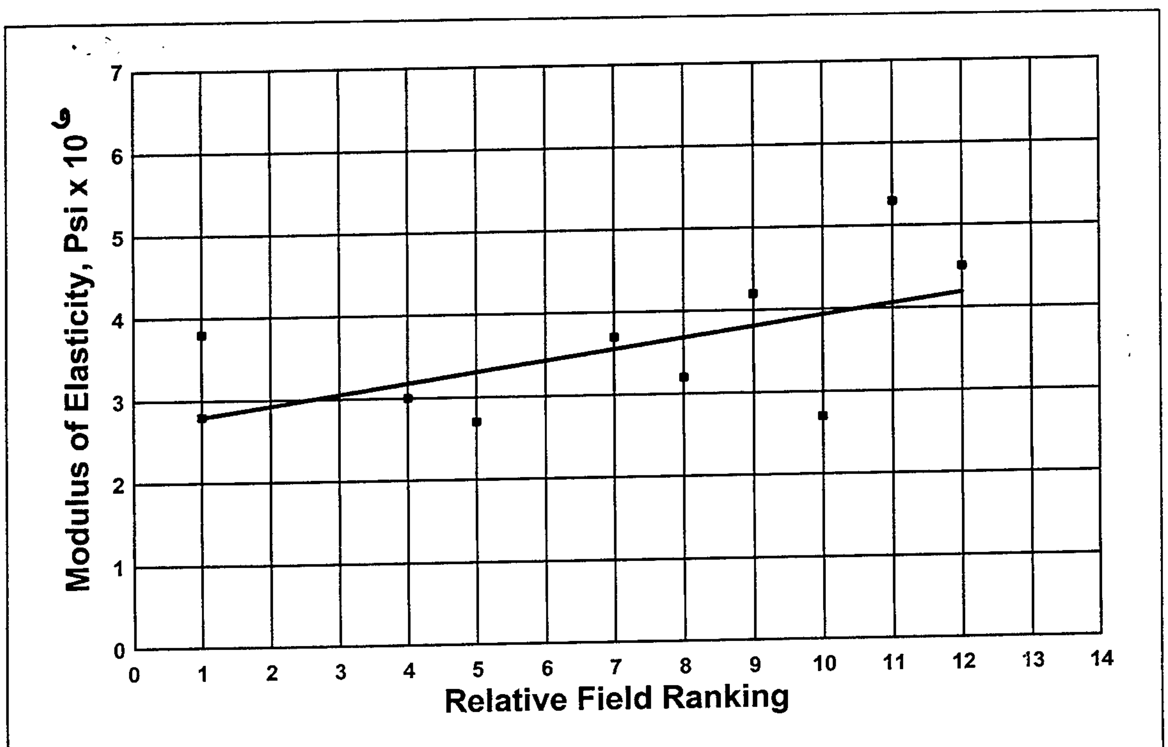


Figure 25. Correlation between modulus of elasticity and field performance (divide psi by 145 to obtain MPa)

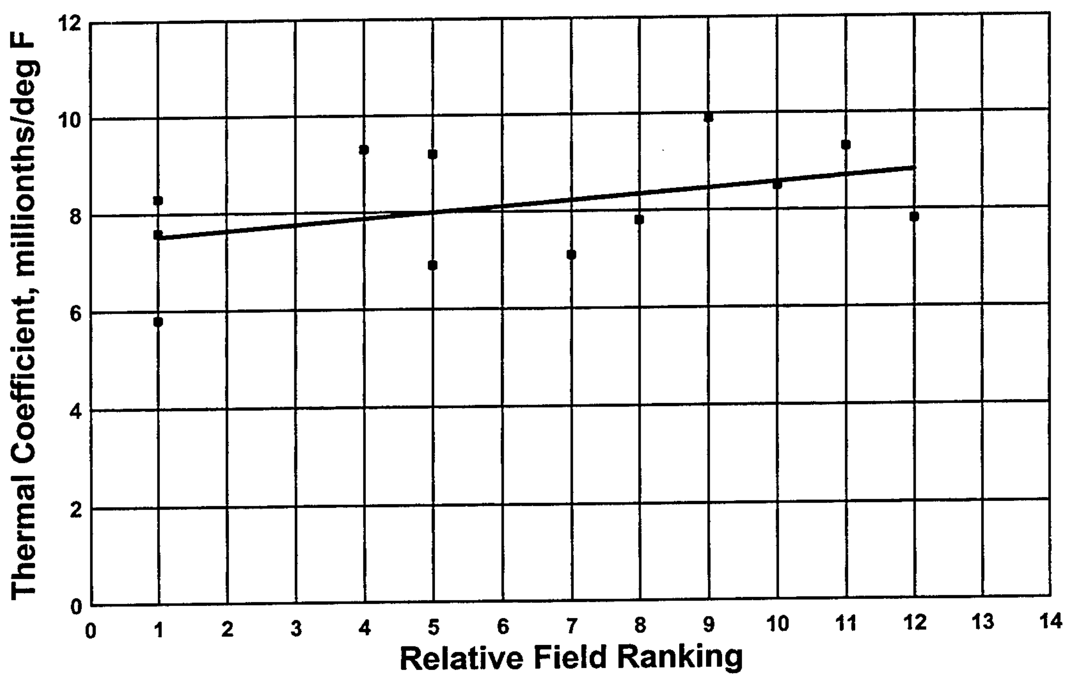


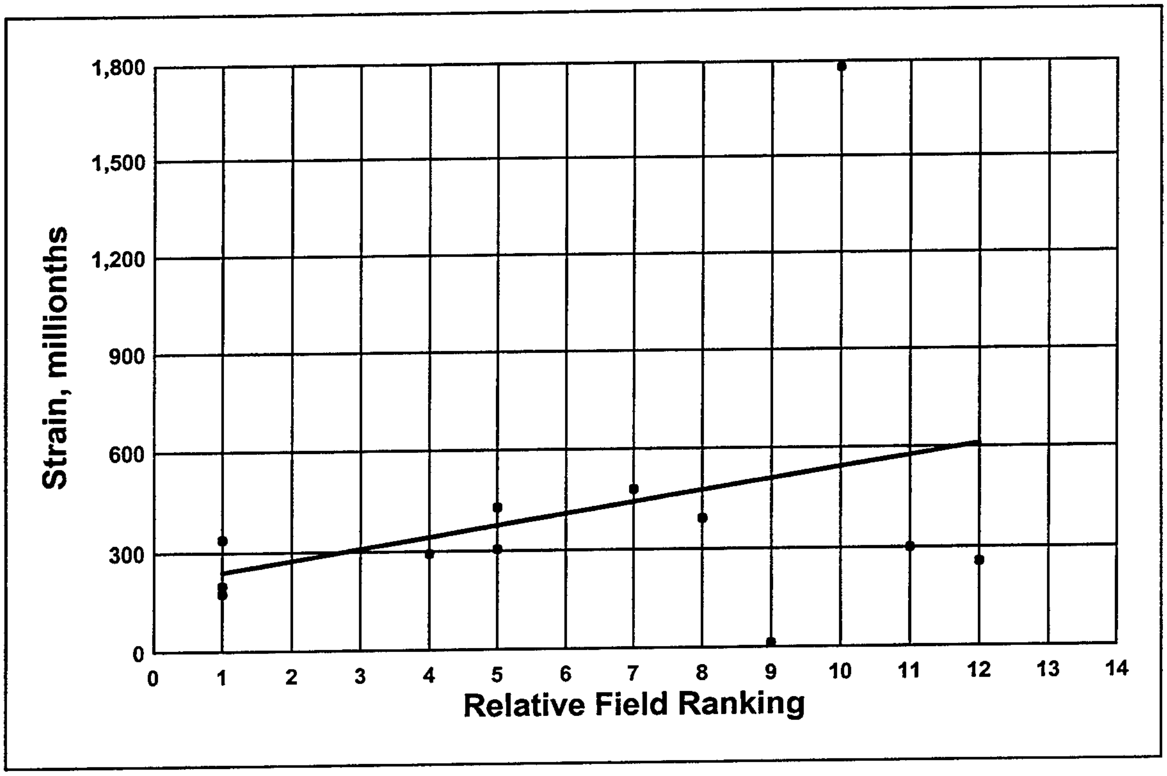
Figure 26. Correlation between coefficient of expansion and field performance (multiply °F by 1.8 to obtain °C)

(18 millionths/deg C) (9.9 millionths/deg F)), the highest coefficient of all materials tested. This property would be expected to have a significant impact on field performance under widely varying ambient temperatures in contrast to stable laboratory conditions.

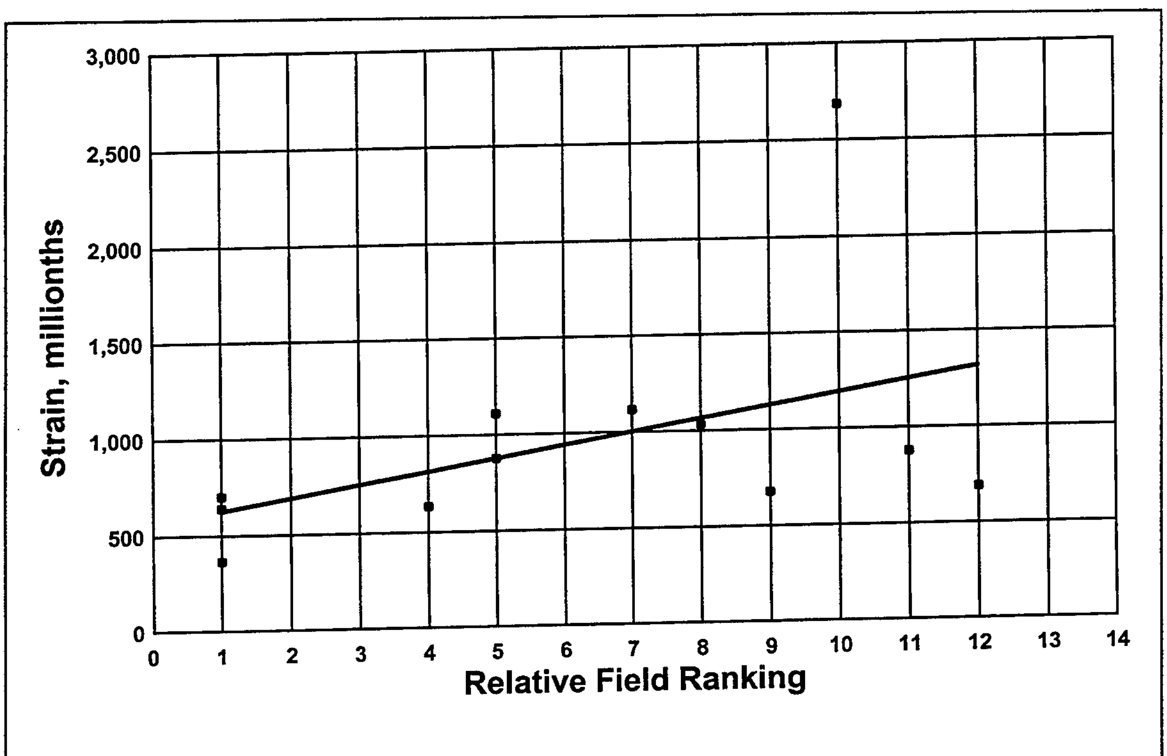
Coefficients of thermal expansion, determined in accordance with ASTM C 531 (1994h), were higher than anticipated and generally higher than that normally associated with concrete. The proposed performance criteria limits coefficient of thermal expansion, determined in accordance with CRD-C 39 (WES 1949), to a maximum of 13 millionths/deg C (7 millionths/deg F).

Unrestrained shrinkage

Overall, there was no significant correlation between unrestrained drying shrinkage at 28-days age and field performance, although the trend was for improved field performance with decreasing shrinkage (Figure 27a). Attempts to correlate peak drying shrinkage with field performance yielded similar results (Figure 27b). However, excluding the materials that demonstrated unsatisfactory field performance, there was a significant correlation between both 28-day and peak drying shrinkage and field performance (Figure 28). The proposed



a. 28-day shrinkage



b. Peak shrinkage

Figure 27. Correlation between drying shrinkage and field performance

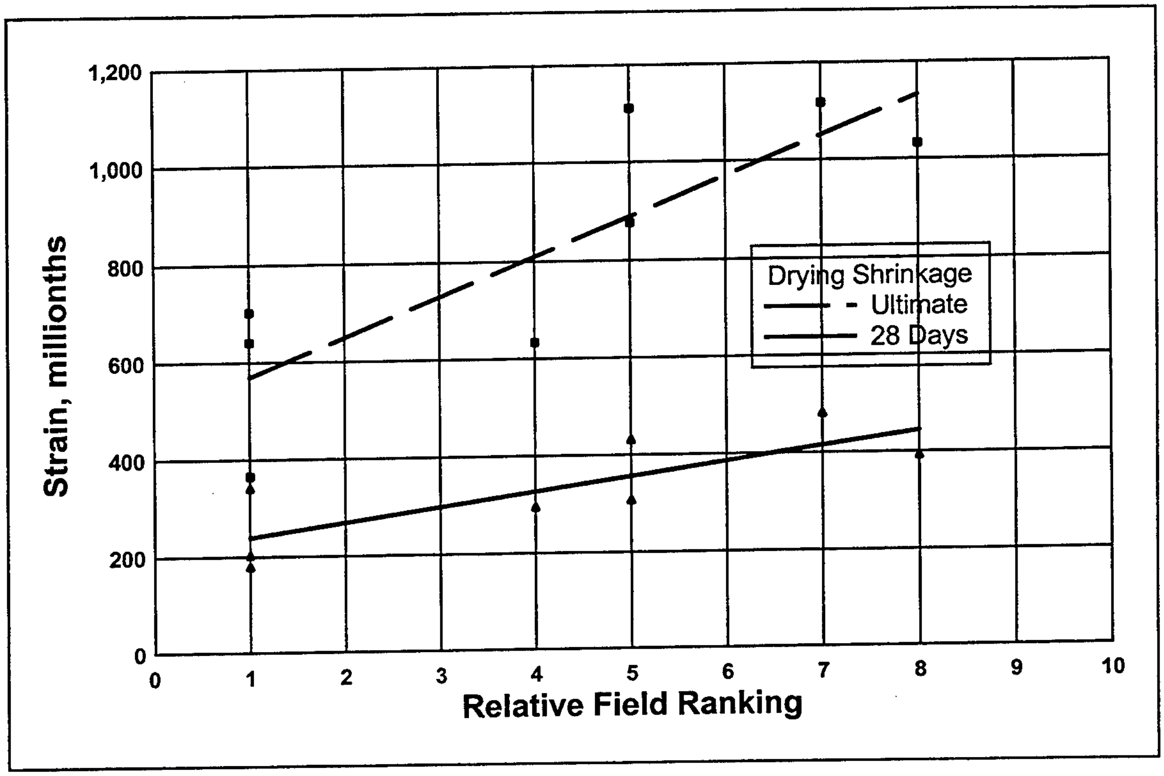
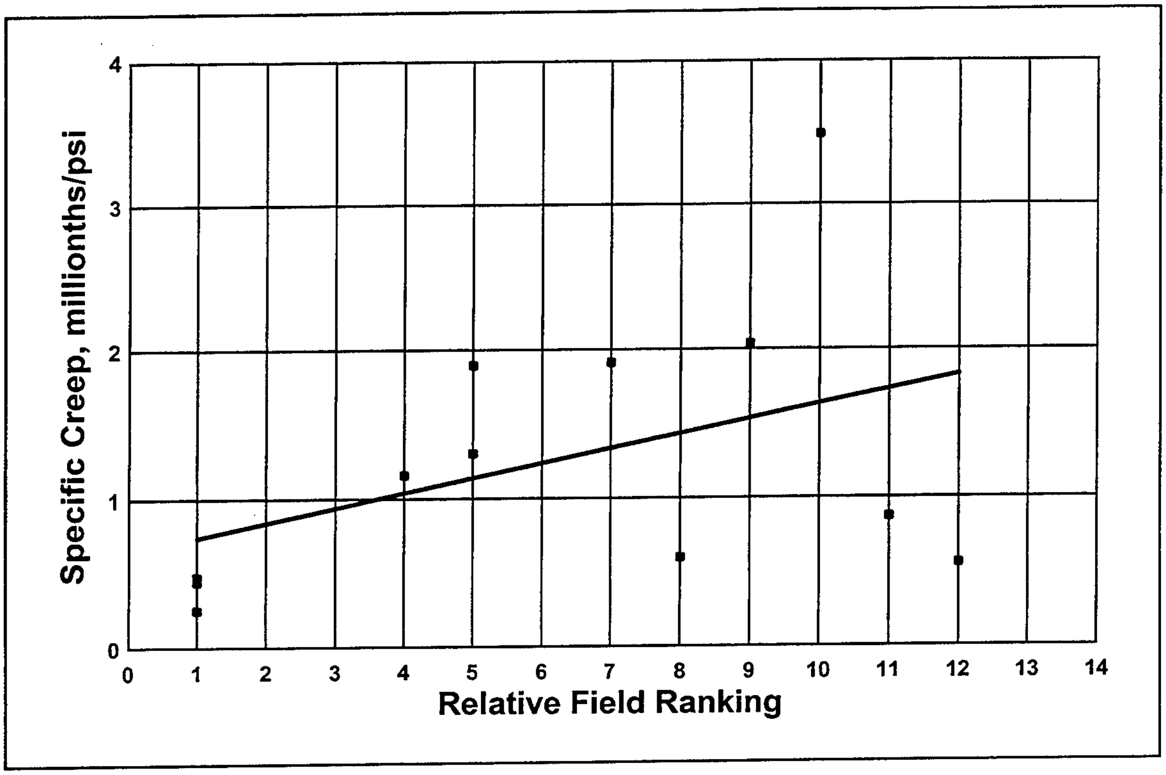


Figure 28. Correlation between drying shrinkage of acceptable materials and field performance

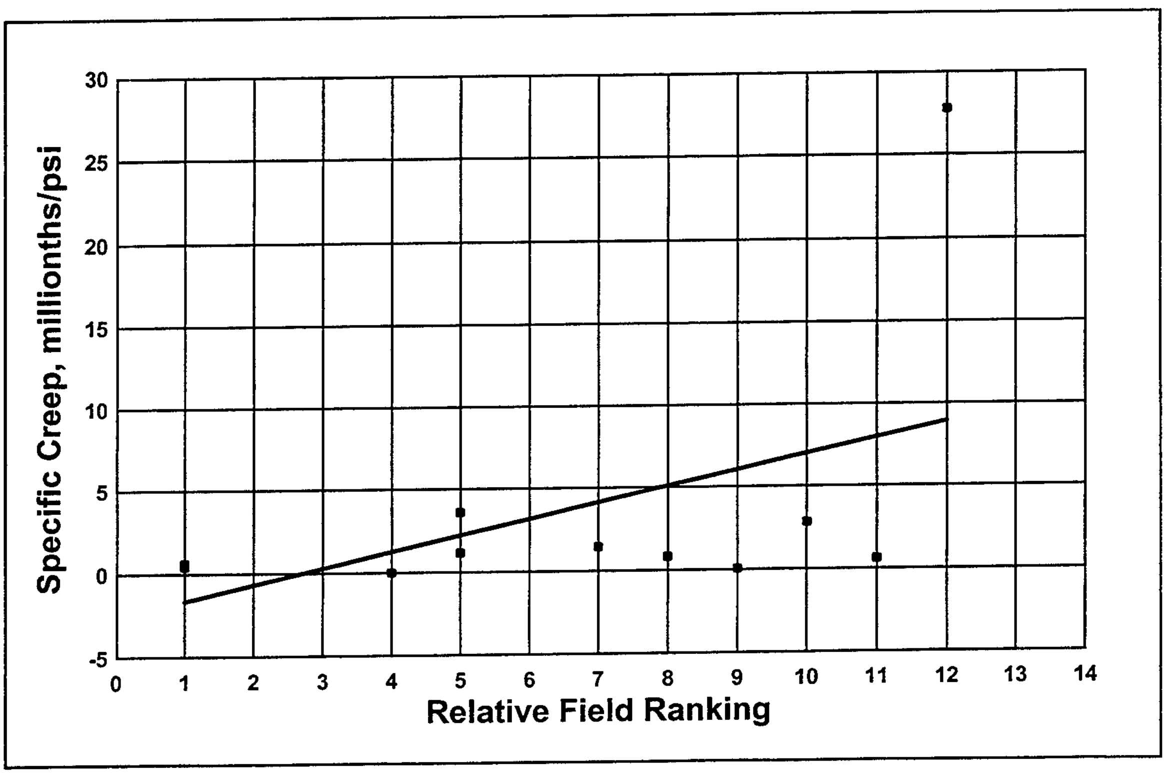
performance criteria limits drying shrinkage at 28-days age to a maximum of 400 millionths. In addition, the criteria limits the peak (ultimate) drying shrinkage to a maximum of 1,000 millionths at 1 year.

Creep

Results of this study appear to contradict the generally accepted theory that higher creep aids in relaxation of stresses and strains induced by restrained shrinkage in concrete repairs, thus reducing the potential for cracking. Although there was no significant correlation between either compressive or tensile creep and field performance, the trend in each case was for improved field performance with decreased creep (Figure 29). These unexpected results are attributed in part to the generally higher drying shrinkage associated with the materials that exhibited high creep characteristics (Figure 30). Apparently, the higher strains induced by increased drying shrinkage more than offset any additional strain relaxation because of increased creep. It is clear that materials proportioned for high creep will be effective in repair only if the drying shrinkage of the material is not proportionately higher. Additional research is necessary to quantify the effect of creep on cracking resistance of repair materials.

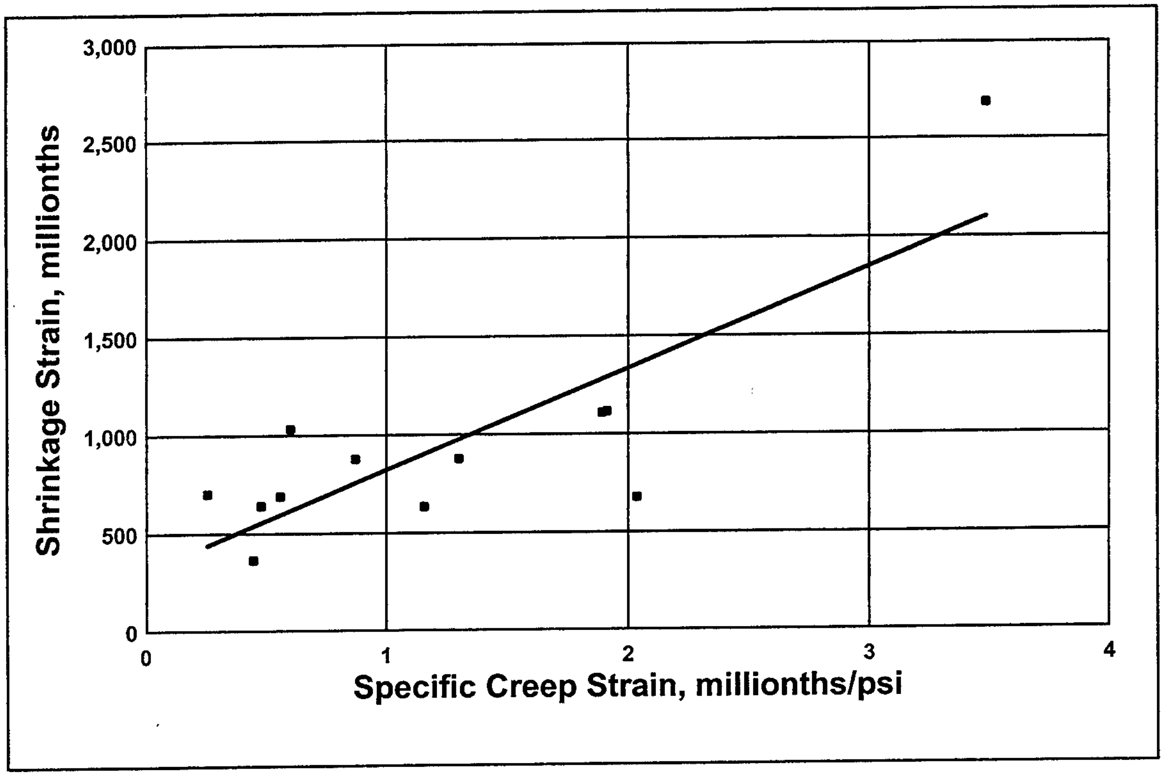


a. Compressive creep

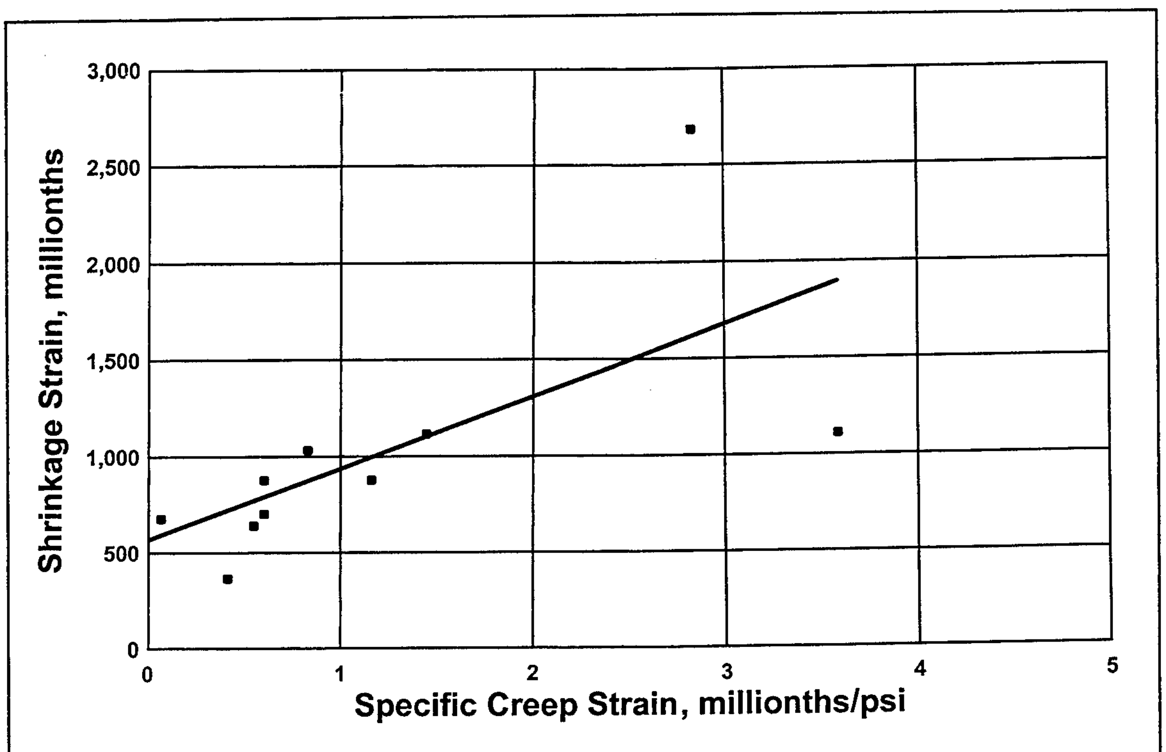


b. Tensile creep

Figure 29. Correlation between creep and field performance (divide psi by 145 to obtain MPa)



a. Compressive creep



b. Tensile creep (excluding Material 5)

Figure 30. Correlation between peak drying shrinkage and creep (divide psi by 145 to obtain MPa)

Restrained shrinkage

Three restrained shrinkage tests were conducted as previously described. All except Materials 10 and 12 exhibited cracking in the ring test, because shrinkage strains induced during drying exceeded the tensile strain capacity at the time. The common features of these two materials were relatively high flexural and tensile strengths (especially the 7-day tensile strength), modest modulus of elasticity, low ultimate shrinkage, and high compressive creep. Most likely the combination of all or some of these properties are critical for resistance of materials to cracking.

In contrast to its good performance in the laboratory, Material 10 exhibited unsatisfactory crack resistance in the field tests. This poor performance is attributed in part to the highest coefficient of thermal expansion of all materials, a property that would be much more significant under widely varying field temperatures compared to controlled laboratory conditions. Material 12 exhibited good crack resistance in field tests. The remaining materials exhibited first cracks in the ring test at ages ranging from 4 to 140 days. The average age at first crack of materials with acceptable field performance was 33 days. However, excluding Material 4, the ages at first crack ranged from 8 to 23 days with an average age of 15 days. In comparison, the average age at first crack of materials with unsatisfactory field performance was only 7 days. The proposed performance criteria require that repair materials exhibit no cracking during the initial 14 days of restrained shrinkage.

The widths of cracks in the ring test specimens were measured periodically and implied shrinkage strains were computed by dividing the sum of the crack widths by the circumference of the ring. Overall, there was a significant correlation between restrained shrinkage strains and both 28-day and peak values of unrestrained drying shrinkage (Figure 31). Also, there was a modest correlation between calculated strains and field performance (Figure 32). Implied strains for those materials with acceptable field performance ranged from 364 to 1,222 millionths with an average of 752 millionths. In contrast, implied strains for those materials with unsatisfactory field performance ranged from 840 to 3,414 millionths with an average of 2,021 millionths. The proposed performance criteria limits implied strain to a maximum of 1,000 millionths at age of 1 year.

In the German angle test, restrained shrinkage specimens were monitored for crack formation under laboratory and field exposure conditions. Field test results indicate that the German angle test can provide a general assessment of a material's resistance to cracking when the test specimens are exposed to varying exposure conditions. Eight of the twelve materials exhibited cracks in field tests with this method. In contrast to the field tests, none of the materials cracked when German angle test specimens were exposed in a controlled laboratory environment. Consequently, this test appears to offer minimal potential for prediction of field performance based on laboratory tests unless the anticipated service conditions can be simulated in the laboratory.

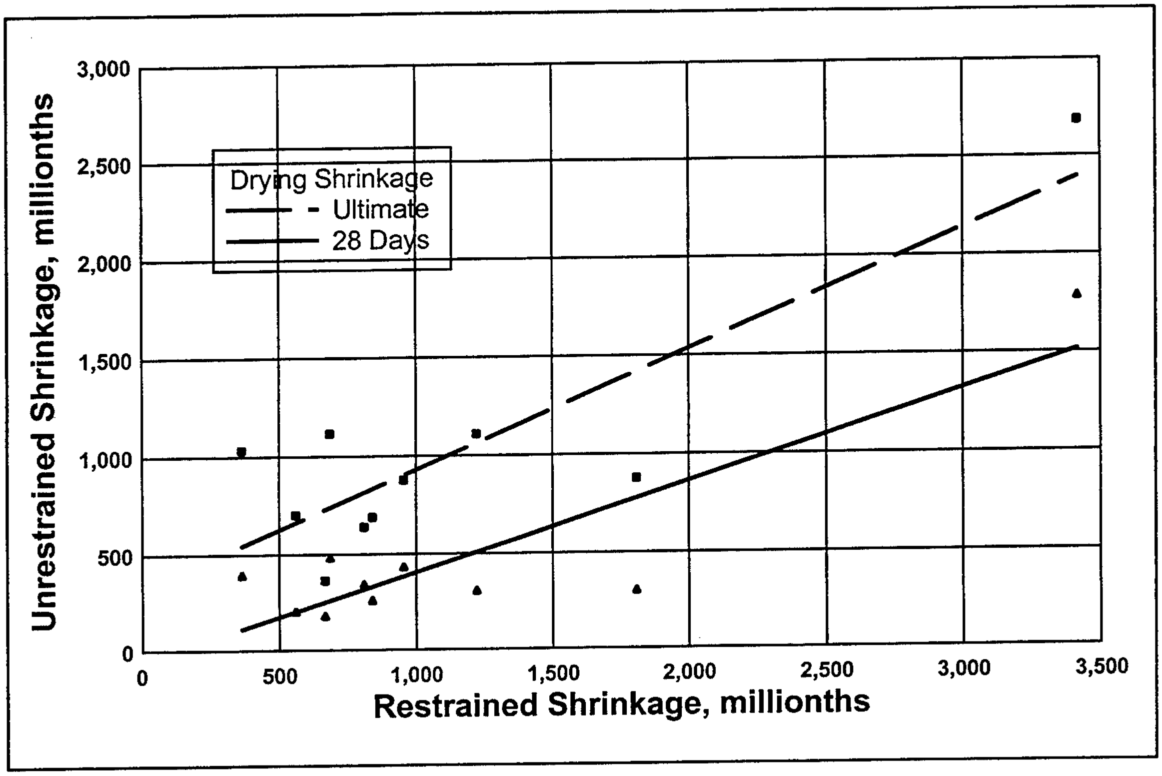


Figure 31. Correlation between unrestrained and restrained drying shrinkage

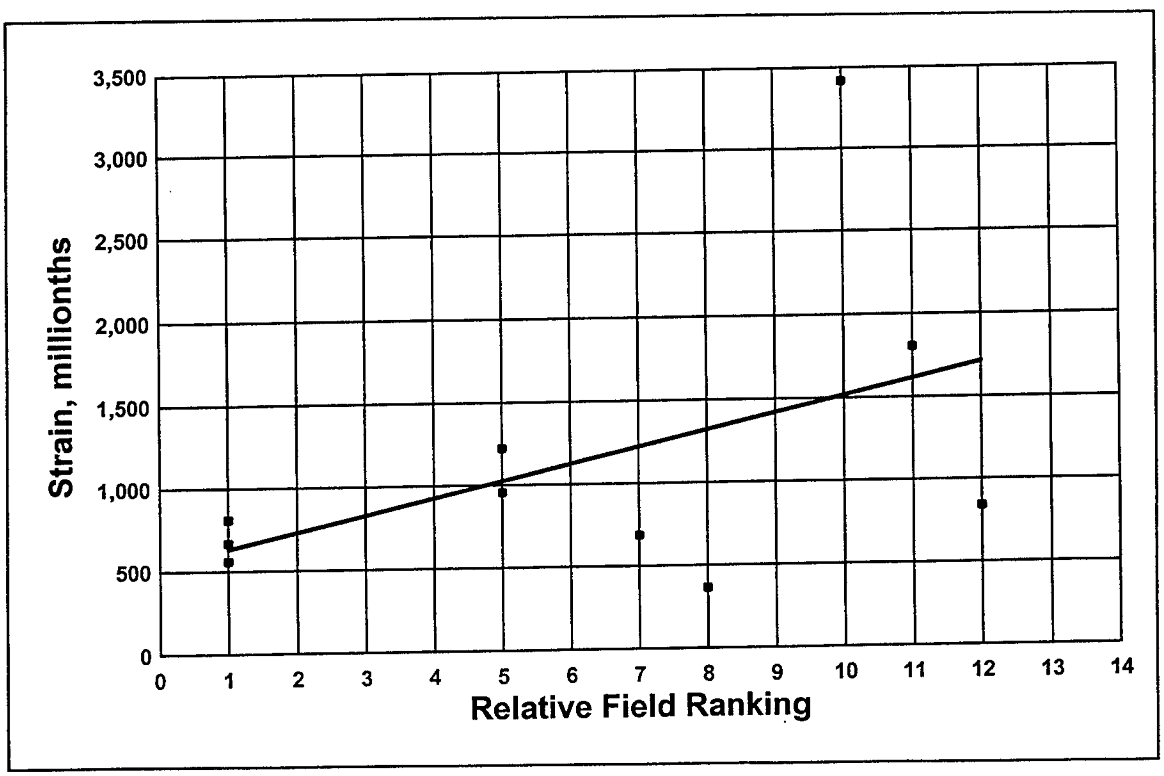


Figure 32. Correlation between restrained shrinkage and field performance

Overall, there was no significant correlation between SPS plate test deflections measured in controlled laboratory conditions and field performance, although the trend was for improved field performance with decreasing deflection (Figure 33a). However, excluding the materials that exhibited unsatisfactory performance in field repairs, there was a significant correlation between laboratory test results and field performance (Figure 33b). Also, there was a significant correlation between laboratory plate test deflections and unrestrained drying shrinkage (Figure 34).

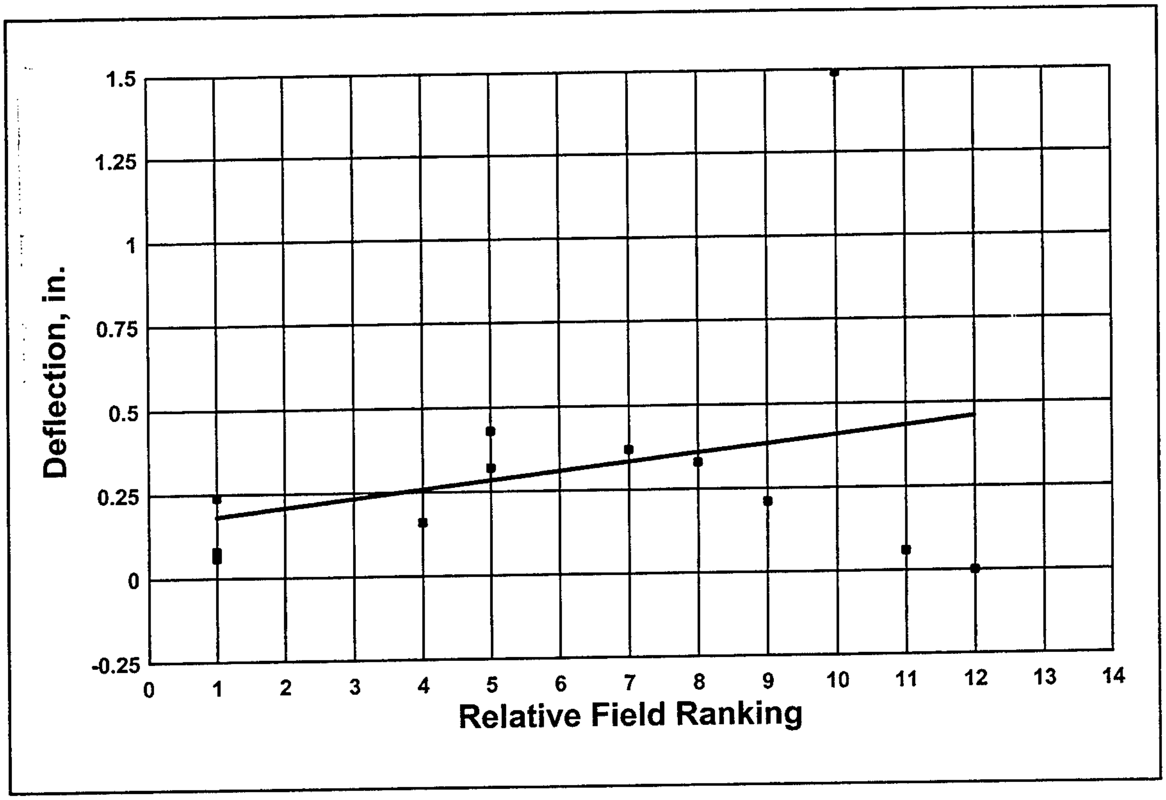
Overall, there was a modest correlation between the results of SPS plate tests conducted in the field and performance of field repairs. Excluding Material 5, which exhibited some cracking attributed to plastic shrinkage and thermal gradients, there was a significant correlation between field test results and performance of field repairs (Figure 35). Test results indicate that the plate test can be used for a general assessment of a material's dimensional compatibility or resistance to cracking; however, modifications to specimen details and instrumentation are necessary to make this promising test more precise.

Performance Criteria

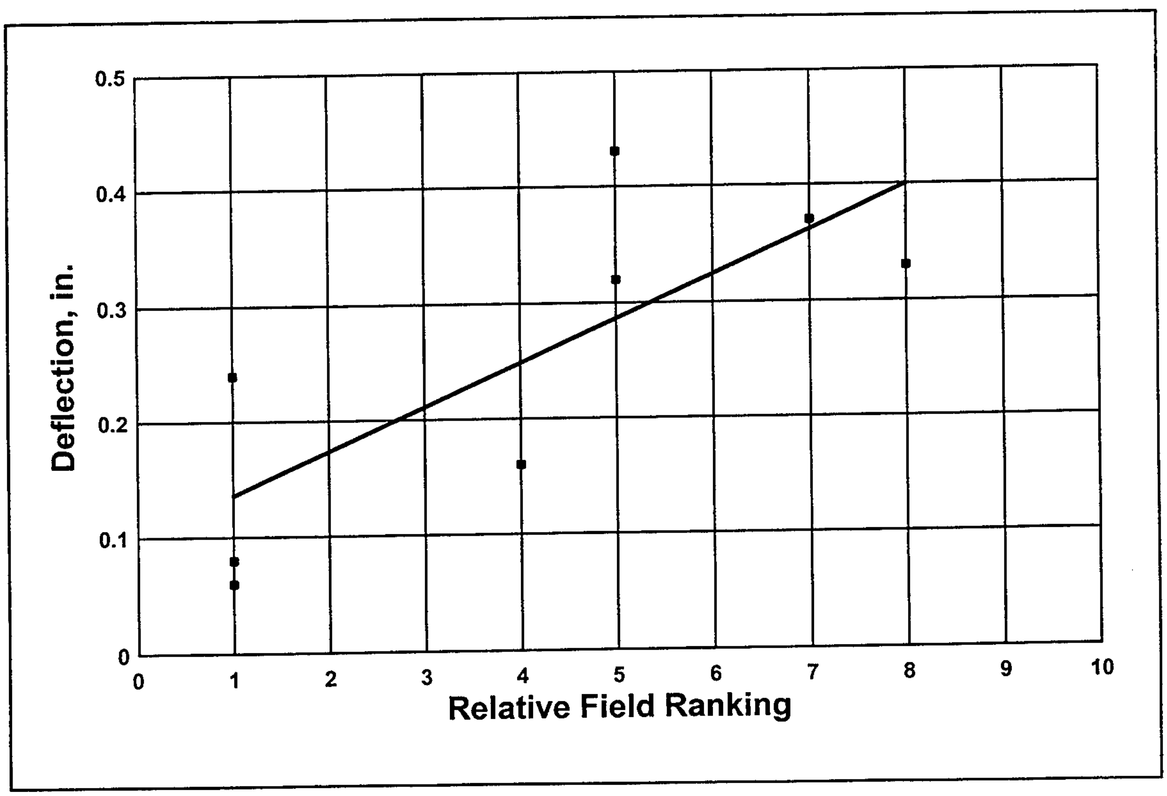
Although there was a general lack of significant correlation between individual material properties and field performance, results of this study indicate that it is possible to predict the field performance of repair materials based on a combination of material properties determined in laboratory tests. Proposed performance criteria for the selection and specification of dimensionally compatible cement-based repair materials discussed in the preceding section are summarized in Table 11. The performance criteria were developed primarily for nonstructural or protective repairs that are the primary concern of this study. In most cases, the success of a repair of this type is dependent on relatively low values for drying shrinkage and modulus of elasticity and relatively high values for tensile stress/strain capacity. Consequently, it is inappropriate to use compressive strength as a basis for material selection.

The proposed performance criteria should be considered as a general profile of desired material properties. The relative importance of individual properties will vary depending on the anticipated application and service conditions for a given repair. Therefore, the requirements should be modified as appropriate for a specific repair.

The general lack of significant correlation between individual material properties and field performance emphasizes the need for a comprehensive analytical model to predict the cracking resistance of repair materials. Also, there is a need for new or improved test methods whereby time-dependent strains induced by drying shrinkage and potential for cracking can be accurately quantified. Any such model or test method must consider the interrelationship of pertinent material properties and the relative importance of individual properties.



a. Overall



b. Acceptable materials

Figure 33. Correlation between laboratory SPS plate test deflection and field performance (multiply inches by 25.4 to obtain millimetres)

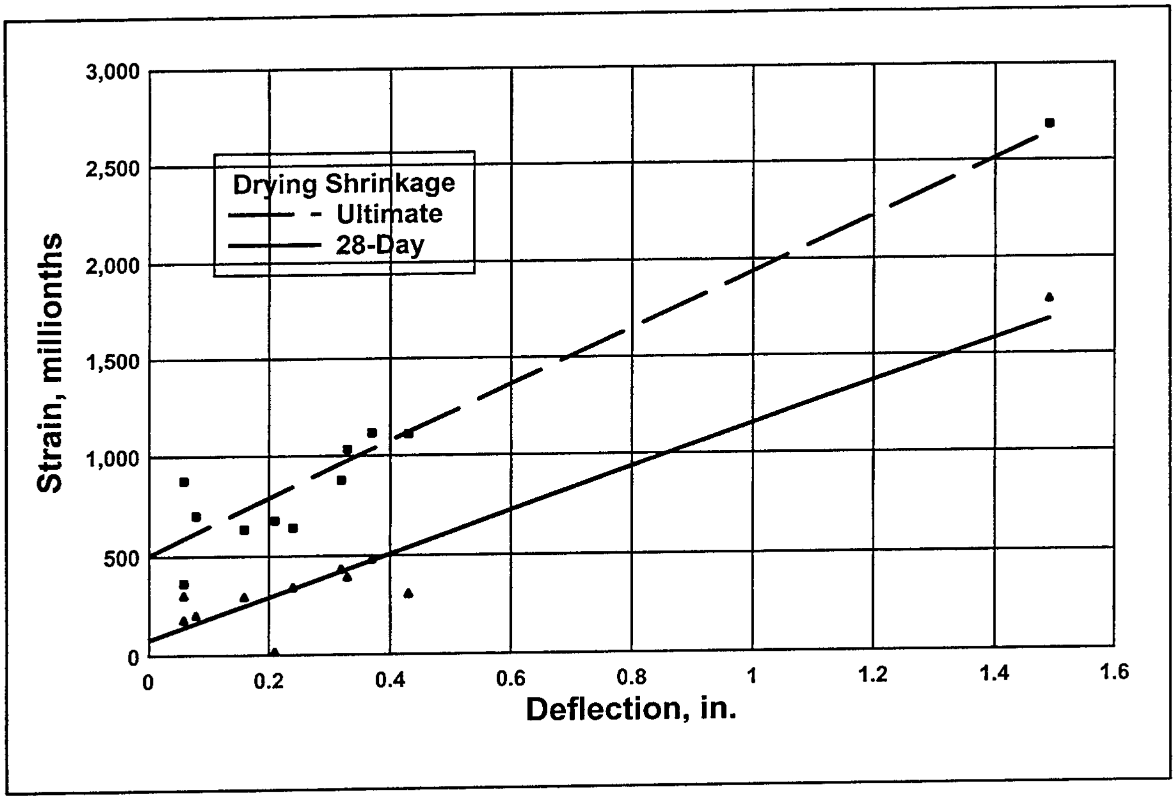


Figure 34. Correlation between laboratory SPS plate test deflection and unrestrained drying shrinkage (multiply inches by 25.4 to obtain millimetres)

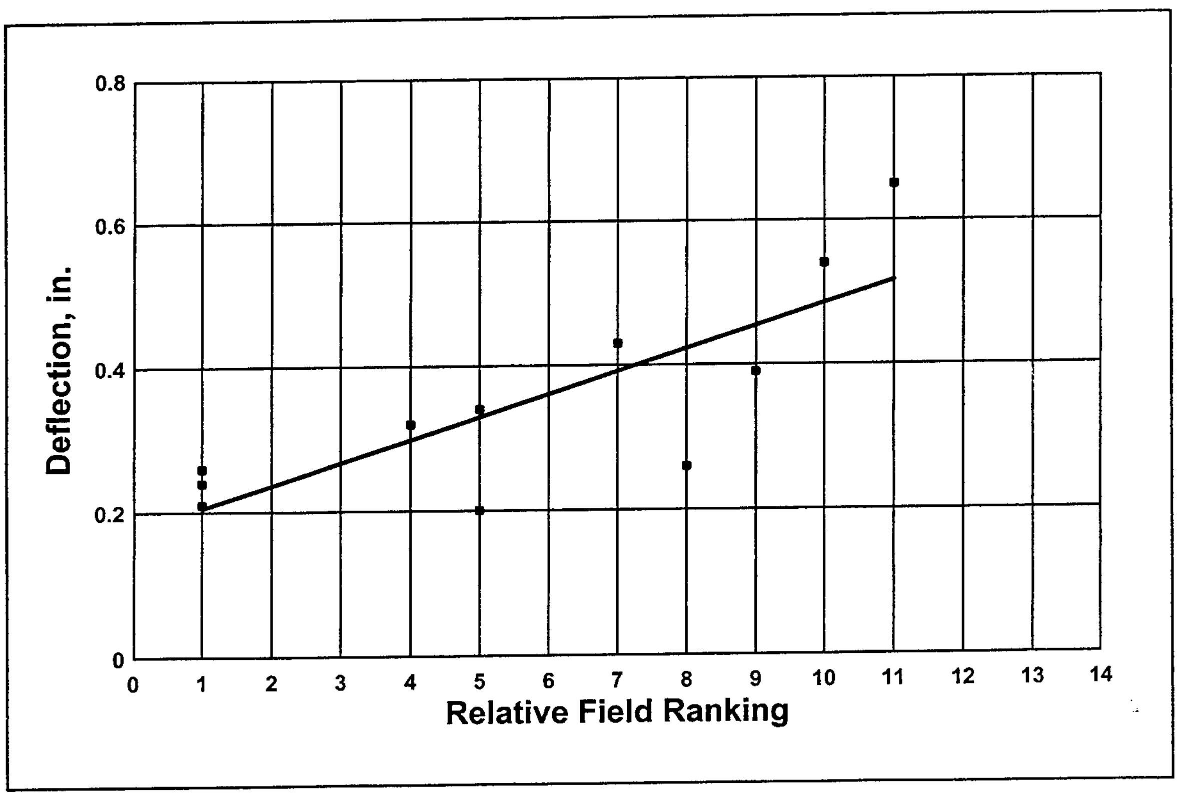


Figure 35. Correlation between field SPS field plate test deflection and field performance (multiply inches by 25.4 to obtain millimetres)

Table 11
Performance Criteria for Repair Materials

Property	Test Method	Requirement
Tensile strength, minimum 28 days	CRD-C 164 (WES 1949b)	2.8 MPa (400 psi)
Modulus of elasticity, maximum	ASTM C 469 (1994f)	24 GPa (3.5×10^6 psi)
Coefficient of thermal expansion, maximum	CRD-C 39 (WES 1949a)	13 millionths/deg C (7 millionths/deg F)
Drying shrinkage, maximum 28 days 1 year	ASTM C 157 (1949e) (Modified). For modifications to the standard, see "Data Sheet Protocol"	 400 millionths 1,000 millionths
Restrained shrinkage - cracking - implied strain at 1-year age, maximum	Ring method. For test description, see "Data Sheet Protocol," Appendix A	 No cracks within 14 days 1,000 millionths

4 Material Data Sheet Protocol

Material data sheets from numerous manufacturers and suppliers in North America were evaluated during the selection of the 12 repair materials for this study. It was obvious from this evaluation that the engineer has very limited and, sometimes, misleading information on which to base selection and specification of materials for a particular repair project. Typically, only data on these properties favorable to the particular material are reported. Test procedures used by the manufacturers vary widely. Such information does not provide user confidence in the given properties and is not a credible basis for selection of materials that will result in durable repairs. Obviously, there is a pressing need for a standard material data sheet protocol. Based on the performance criteria developed in this study and lessons learned, such a repair material data sheet protocol is proposed (Table 12). The properties and their ranges and applicable test methods critical for selection of material for protective repairs based on their dimensional compatibility with existing concrete are as defined in Table 11.

It is emphasized that it is not, in the end, a material per se that one seeks: it is a certain combination of necessary properties. Material data sheets must provide reliable information necessary to select this combination of material properties. Materials must be dimensionally compatible with the existing concrete in the structure to be repaired. Therefore, material properties and related information must be presented in such a manner that a material's ability to resist cracking can be accurately evaluated. Also, the potential for application and service problems resulting from variations in material properties caused by changes in environmental conditions should be emphasized.

The proposed data sheet protocol includes requirements for data on basic material composition and limitations of the material under specific application and service conditions. The choice of the best material for a given application is, of necessity, an optimization. Therefore, to be successful, the optimization process must be conducted with a complete knowledge of the relevant material properties. Material data sheets must become the reliable source of this information.

The proposed data sheet protocol embraces the material manufacturers and suppliers, contractors, designers and specifiers, and the owner with the aim of addressing the various problems which are currently encountered in the material selection process.

Table 12
Repair Material Data Sheet Protocol

1. Repair Material Description

- Recommended use
- Benefits
- Limitations

2. Composition Data

- Base material(s)
- Sulfur trioxide (SO_3), % - ASTM C 563 (1994i)
- Alkali content, kg/m^3 (lb/yd^3)
- pH
- Air content

3. Physical Properties

- Unit weight, kg/m^3 (lb/ft^3)
- Fresh wet density – ASTM C 138 (1994d)
- Strengths

Property and Test Method	Age, days			
	1	3	7	28
Compressive strength - Mortar – ASTM C 109 (1994c) 51- mm (2-in.) cubes - Concrete; mortar expanded with aggregate – ASTM C 39 76 x 152 mm (3 x 6 in.)				
Flexural Strength – ASTM C 78 (1994b) - Mortar - Concrete; mortar expanded with aggregate				
Direct tensile strength – CRD-C 164 (WES 1949b) - Mortar - Concrete; mortar expanded with aggregate				

- Modulus of elasticity – ASTM C 469 (1994f)
  - Mortar
  - Concrete; mortar expanded with aggregate

(Continued)

Table 12 (Concluded)

4. Performance Properties

- Drying shrinkage - ASTM C 157 (1994e) (Modified[1])
  - Mortar
  - Concrete; mortar expanded with aggregate
- Coefficient of thermal expansion – CRD C 39 (WES 1949a)
  - Mortar
  - Concrete; mortar expanded with aggregate
- Freezing and thawing resistance – ASTM C 666 (1994k) (Procedure A)
- Compressive creep – ASTM C 512 (1994g)
  - Mortar
  - Concrete; mortar expanded with aggregate
- Rapid chloride permeability – ASTM C 1202 (1994m)
  - Mortar
  - Concrete; mortar expanded with aggregate
- Sulfate resistance – ASTM C 1012 (1994l)
- Cracking resistance – Ring Test[1]
  - Age of first crack
  - Implied strain
    (Sum of crack widths at the end of test divided by the ring circumference)
  - Age at the end of the test
- Cracking resistance – German Angle[1]

5. Packaging, storage

- Packaging
- Volume yield
- Shelf life
- Storage requirements

6. How the Material Works

7. How to Use the Material

- Concrete surface preparation
- Mixing
- Application and finish
- Curing
- Cleanup
- Safety

[1] See Appendix A for commentaries to the Material Data Sheet Protocol.

5 Conclusions

The objective of this project was to develop performance criteria for selection of repair materials that are dimensionally compatible with existing concrete. One approach to ensure that repaired concrete structures are performing their intended function for the designed service life is to minimize cracking in repairs. Guidance for selection of repair materials that would reduce the risk of premature failures was developed in this study. This guidance includes a standard protocol for repair material data sheets and performance criteria for evaluation of alternative materials and specification of those materials with optimum properties. A better understanding of the fundamental nature of dimensional compatibility in concrete repair along with the proposed performance criteria and standard protocol for material data sheets should lead to fewer premature failures, greater composite durability and, therefore, more cost-effective use, and possibly more innovative materials. Specific conclusions and recommendations based on the results of this study are summarized in the following text.

Although there was a general lack of significant correlation between individual material properties and field performance, results of this study indicate that it is possible to predict the field performance of repair materials based on a combination of material properties determined in laboratory tests. The relative importance of individual properties will vary depending on application and service conditions for a given repair; therefore, the requirements should be modified as appropriate for a specific repair.

The general lack of significant correlation between individual material properties and field performance emphasizes the need for a comprehensive analytical model to predict the cracking resistance of repair materials. Any such model must consider the interrelationship of pertinent material properties, the relative importance of individual properties, and the effect of environmental conditions on time-dependent material properties. A reliable model will allow for significant improvements in selection of dimensionally compatible repair materials that will combine with the existing concrete in a composite system that will ensure acceptable long-term service.

Results of this study illustrate the significant effect of volume change and drying shrinkage, in particular, on the performance of restrained repair materials. While there was a general correlation between the results of laboratory tests on unrestrained shrinkage specimens and field performance, there is a need for new or improved restrained shrinkage tests to evaluate the cracking resistance of repair materials. A modest correlation between results of the ring test and field performance indicates that further evaluation and development of this type of test is warranted. The potential for replacement of the steel ring with a concrete core should be investigated. Test results indicate that the SPS plate test can be used for a general assessment of a material's dimensional compatibility, or resistance to cracking; however, modifications to specimen details and instrumentation are necessary to make this promising test more precise.

Results of this study appear to contradict the generally accepted theory that higher creep aids in relaxation of stresses and strains induced by restrained shrinkage in concrete repairs, thus reducing the potential for cracking. These unexpected results are attributed in part to the significant correlation between higher creep and drying shrinkage of the materials tested. Apparently, the higher strains induced by increased drying shrinkage more than offset any additional strain relaxation because of increased creep. Additional research is necessary to quantify the effect of creep on cracking resistance of repair materials. This research must address the experimental difficulties encountered when a uniaxial tensile load is required and strains have to be measured very accurately, especially in a material that is drying under load and shrinkage is the predominant deformation. The potential for using total deformation of a drying specimen under tensile load to predict material performance in protective repairs should be investigated.

Obviously, all repair problems cannot be resolved only by improvements in repair materials. The evaluation of existing concrete condition, design input, and the quality of workmanship are also of fundamental importance in ensuring the durability of repaired structures. Also, application and service conditions can have a significant effect on ultimate properties of the repair material. Therefore, it should be determined that the material properties required by the performance criteria can actually be achieved under the prevailing site conditions. Such a determination emphasizes the need for adoption of the standard protocol for material data sheets as a basis to evaluate the relevance and reliability of test methods and data. Although adoption of the proposed material data sheet protocol will provide some necessary solutions to current problems, the ultimate goal is to establish formalized and authoritative codes of practice and accepted standards for performance criteria.

Results of this study demonstrate that the formation and severity of cracking depends not only on the repair material but also on such factors as mixture proportions and construction operations - mixing, placing, consolidation, finishing, and curing. The choice of material cannot be made independently of the choice of process by which the material is to be placed, finished, and cured. The selection and application of the best material for a particular project is no substitute for using good quality workmanship.

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c. ASTM C 109. "Test method for compressive strength of hydraulic cement mortars (using 2-in. or 50-mm cube specimens)."

d. ASTM C 138. "Test method for unit weight, yield, and air content (gravimetric) of concrete."

e. ASTM C 157. "Test method for length change of hardened hydraulic-cement mortar and concrete."

f. ASTM C 469. "Test method for static modulus of elasticity and Poisson's ratio of concrete in compression."

g. ASTM C 512. "Test method for creep of concrete in compression."

h. ASTM C 531. "Test method for linear shrinkage and coefficient of thermal expansion of chemical-resistant mortars, grouts and monolithic surfacings."

i. ASTM C 563. "Test method for optimum SO_3 in portland cement."

j. ASTM C 596. "Test method for drying shrinkage of mortar containing portland cement."

k. ASTM C 666. "Test method for resistance of concrete to rapid freezing and thawing."

l. ASTM C 1012. "Test method for length change of hydraulic-cement mortars exposed to a sulfate solution."

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a. CRD-C 39, "Test method for coefficient of linear thermal expansion of concrete."

b. CRD-C 164, "Standard test method for direct tensile strength of cylindrical concrete or mortar specimens."

Appendix A
Data Sheet Protocol

Repair Material Data Sheet Protocol and Commentaries

1. Repair Material Description

- Recommended use
- Benefits
- Limitations

2. Composition Data

- Base material(s)

Example: This repair mortar is composed of precise blend of portland cement, microsilica, graded aggregates, dry acrylic polymer, and fine fibers.

- Sulfur trioxide (SO_3), % - ASTM C 563 (1994i)
- Alkali content, kg/m^3 (lb/yd^3)

The typical means by which the alkali content has been controlled with concrete mixtures in the United States has been to establish a maximum limit only on the portland cement. Cement with an alkali content smaller than 0.6 percent, expressed as equivalent Na_2O, is referred to as low alkali cement. This provision proved satisfactory for concrete. The disadvantage of establishing an alkali limit based on the alkali of the portland cement alone for repair materials is that many proprietary repair materials contain blends of different cements, additives, admixtures, and other constituents which contain alkali. It is the sum of the alkalies from all sources that is pertinent to the potential reaction with a reactive aggregate.

Past research conducted first in Germany, and then in Canada, led to the conclusion that when the alkali in a mixture is kept below a maximum of 3.0 kg/m^3 (5.0 lb/yd^3), there will be no ASR (Publication No. FHWA-SA-97-045, Gress, D., "Early Distress of Concrete Pavements," January 1997 (Gress 1997).

- pH
- Air content

3. Physical Properties

- Unit weight of material, kg/m^3 (lb/ft^3)
- Fresh wet density – ASTM C 138 (1994d)
- Strengths

Property and Test Method	Age, days 1	3	7	28
Compressive strength - Mortar – ASTM C 109 (1994c) 51-mm (2-in.) cubes - Concrete mortar expanded with aggregate – ASTM C 39 (1994a) 76 x 152 mm (3 x 6 in.)				
Flexural Strength – ASTM C 78 (1994b) - Mortar - Concrete; mortar expanded with aggregate				
Direct tensile strength – CRD-C 164 (WES 1949b) - Mortar - Concrete; mortar expanded with aggregate				

- Modulus of elasticity – ASTM C 469 (1994f)
  - Mortar
  - Concrete; mortar expanded with aggregate

4. Performance Properties

- Drying shrinkage - ASTM C 157 (Modified) (1994e)

Modifications to ASTM C 157

ASTM C 157, Length Change of Hardened Hydraulic Cement Mortar and Concrete, as modified below:

a. ***Standard specimen size is 76 x 76 x 275 mm (3 x 3 x 11-¼ in.) for concrete mortar expanded with aggregate and mortar.***

b. ***Remove sample from mold at 23 ± ½ hours and make initial comparator reading immediately. (For rapid hardening materials, remove sample from mold at 3 hours and make initial comparator reading).***

c. ***The specimens are then stored under the standard conditions of 24.0 ± 1.7°C (73.4 ± 3°F) and 50 ± 4% pH.***

Subsequent comparator readings are to be taken at ages of 3 days, 7 days, 14 days, 1 month, 2 months; measurements shall continue until 90% of ultimate drying shrinkage is reached. Ultimate shrinkage is to be determined as described in ASTM C 596 (1994j), Drying Shrinkage of Mortar Containing Portland Cement.

- Mortar
- Concrete; mortar expanded with aggregate

- Coefficient of thermal expansion – CRD C 39 (WES 1949a)
  - Mortar
  - Concrete; mortar expanded with aggregate
- Freezing and thawing resistance – ASTM C 666 (Procedure A (1994k)
- Compressive creep – ASTM C 512 (1994g)
  - Mortar
  - Concrete; mortar expanded with aggregate
- Rapid chloride permeability – ASTM C 1202 (1994m)
  - Mortar
  - Concrete; mortar expanded with aggregate
- Sulfate resistance – ASTM C 1012 (1994l)
- Cracking resistance – Ring Test

Description of the Ring Test

This method allows the determination of materials sensitivity to cracking caused by restrained volume changes. Figure 1A shows the mold for the ring test. The material is cast around a 254-mm-(10-in.-) diameter, 25.4-mm (1-in.) steel pipe. The thickness of the tested material ring is 32 mm (1.25 in.), the height is 102 mm (4 in.). Material mix in the mold should be consolidated as recommended by the manufacturer. The material rings are to be kept in their molds and covered with plastic for the first 24 hours after they are cast. Having been removed from their molds, the top surface of the ring should be sealed with epoxy. Materials should then be wet cured for 48 hours. After the completion of the recommended curing period, the specimen shall then be kept for a minimum of 60 days under the standard laboratory conditions – 24.0 ± 1.7°C (73.4 ± 3°F) and 50 ± 4% RH. The rings should be monitored daily for evidence of cracking, and the day that cracking is observed should be recorded with precision of 0.04 mm (0.001 in.). Each of the cracks that formed should be measured periodically for width at quarter points and in the middle along the crack and the average width recorded. The computed strain associated with the crack widths at the end of testing is reported in the data sheet (implied strain). This strain is computed by taking the sum of the average crack width of all cracks in the specimen and dividing by the ring circumference – 1,000 mm (39.4 in.)

- Age of first crack
- Implied strain

  (Sum of crack widths at the end of test divided by the ring circumference)
- Age at the end of the test

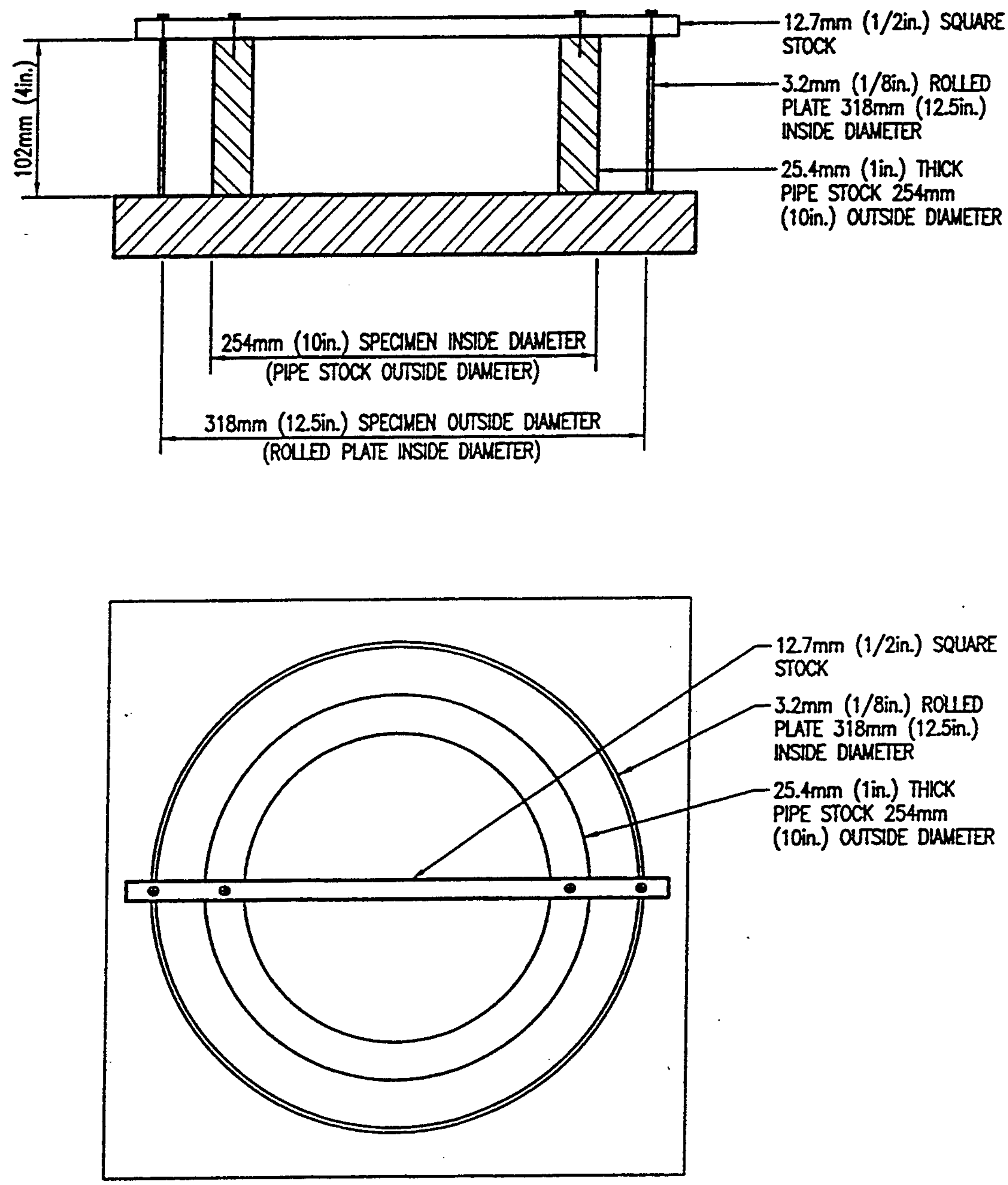

Figure 1A. Ring Test specimen mold

Cracking resistance – German Angle

Description of the German Angle Test

This test was originally developed by the Technical Academy, Aachen, Germany, and adopted as the Technical Test Regulations (TR BE-PCC) for concrete substitution systems made of cement mortar/concrete with a plastic additive by the Highway Construction Department of the Federal Ministry of Transport.

The following is the modification of this test. The mold used for this test is shown in Figure 2A.

Apply epoxy bonding compound before placing repair mix into the angle. Unless the manufacturer recommends otherwise, the mixture is to be compacted by vibration and then to be leveled off and smoothed. The specimen should be wet for 72 hours, then cured under the intended service conditions or laboratory tested under the conditions which simulate intended service conditions. Conditions of the test shall be described in the data sheet. The specimens shall be monitored for cracking for a minimum of 90 days. The time to cracking, number of cracks at the end of the test, and average crack width should be recorded.

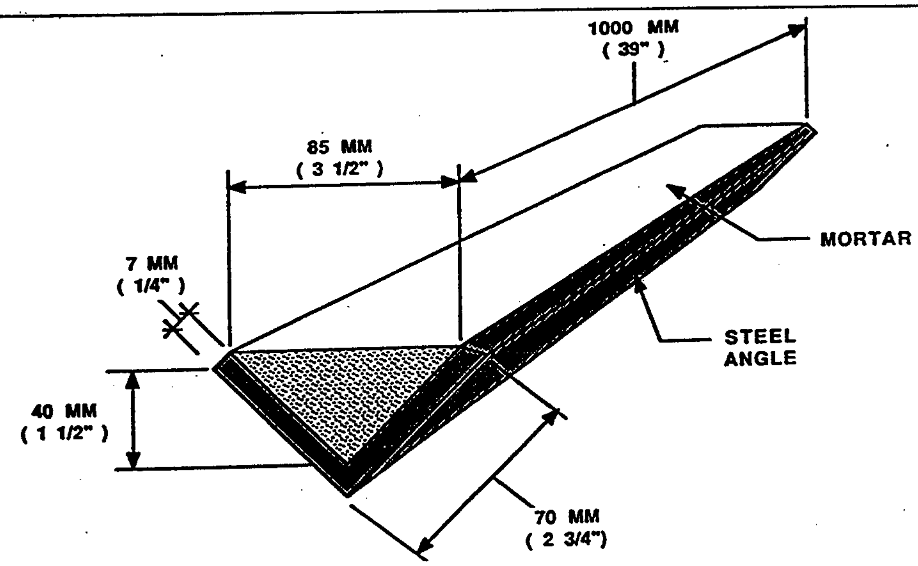

Figure 2A. German Angle Test specimen

5. Packaging, storage

- Packaging
- Volume field
- Shelf life
- Storage requirements

6. How the Material Works

Example:

This product is a medium slump, two-component, trowel grade mortar. The product's portland cement base and low water-to-cement ratio provide the foundation for the system's strength, durability, and basic physical properties. To improve its properties, the product utilizes the advantages of an acrylic polymer emulsion. The fine particle size of the acrylic polymer allows it to penetrate and form a polymer film throughout the C-S-H matrix, and microvoids. This precise filling of the voids reduces shrinkage, permeability, and moisture absorption. Additionally, the polymer increases adhesion, flexibility, and freeze-thaw and abrasion resistance.

7. **How to Use the Material**

- Concrete surface preparation
- Mixing
- Application and finish
- Curing
- Cleanup
- Safety

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13. ABSTRACT *(Maximum 200 words)*

The results of a study to develop performance criteria for cement-based repair materials are summarized herein. Results of laboratory tests and field performance studies were correlated and guidance for selection of repair materials that would reduce the risk of premature failures was developed. This guidance includes a standard protocol for repair material data sheets and proposed performance criteria. Results of this study illustrate the significant effect of drying shrinkage on the performance of restrained repair materials. While there was a general correlation between the results of laboratory tests on unrestrained shrinkage specimens and field performance, there is a need for restrained shrinkage tests to evaluate the cracking resistance of repair materials. Although there was a general lack of significant correlation between individual material properties and field performance, results of this study indicate that it is possible to predict the field performance of repair materials based on a combination of material properties determined in laboratory tests. Results of this study emphasize the need for a comprehensive analytical model to predict the cracking resistance of repair materials that considers the interrelationship of pertinent material properties, the relative importance of individual properties, and the effect of environmental conditions on time-dependent material properties.

14. SUBJECT TERMS

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Cracking	Material data sheets	Repair materials
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